UNIVERSIDAD DE CANTABRIA

ESCUELA DE DOCTORADO DE LA UNIVERSIDAD DE CANTABRIA

DOCTORADO EN INGENIERÍA CIVIL

TESIS DOCTORAL

Desarrollo y aplicación de un enfoque integral de gestión de la construcción, mediante la interacción colaborativa del diseño 5D BIM, la organización multi-flexible de la construcción y los principios de mejora continua

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PhD THESIS

Development and implementation of a comprehensive construction management approach through collaborative interaction of 5D BIM design, multi-flexible construction execution organization, and continuous improvement principles

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Presentada por: **DAVID LEICHT.**

Dirigida por: **Prof./Dr. DANIEL CASTRO FRESNO.**

Prof./Dr. JOAQUÍN DÍAZ.

Santander, 2021

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Affidavit of the Dissertation

I hereby declare that the present thesis has been written independently and under exclusive use of the specified literature and resources. The work has not been submitted to any other examination board in the same or similar form and has not been published anywhere else.[1]

Title of work submitted: Development and implementation of a comprehensive construction management approach through collaborative interaction of 5D BIM design, multi-flexible construction execution organization, and continuous improvement principles.

Steinbach, 29.10.2020

....

Location and date Signature

Parts of the present work have been published in the following article:

Leicht, D., Castro-Fresno, D., Dìaz, J., Baier, C., (2020), "Multidimensional Construction Planning and Agile Organized Project Execution - The 5D-PROMPT Method", MDPI, Basel, Switzerland, Sustainability, 12(16), 6340; Sustainability, doi:10.3390/su12166340

[1] The text of the declaration has been derived from a Declaration-Template provided by the University of Applied Sciences THM; Retrieved at 29.10.2020; 17:21: https://www.thm.de/mni/studium/allgemeines/alle-downloads/studium/studiengaenge/diplom-informatik/downloads-links-dipl-inf.html?start=10.

Declaración jurada de la disertación

Declaro que la presente tesis ha sido escrita independientemente y bajo el uso exclusivo de la literatura y los recursos especificados. El trabajo no ha sido presentado a ninguna otra comisión examinadora en la misma o similar forma y no ha sido publicado en ningún otro lugar.[1]

Título del trabajo presentado: Desarrollo y aplicación de un enfoque integral de gestión de la construcción mediante la interacción colaborativa del diseño 5D BIM, la organización multiflexible de la construcción y los principios de mejora continua.

Steinbach, 29.10.2020

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Lugar y fecha	Firma

Algunas partes del presente trabajo se publicaron en el siguiente artículo:

Leicht, D., Castro-Fresno, D., Dìaz, J., Baier, C., (2020), "Multidimensional Construction Planning and Agile Organized Project Execution - The 5D-PROMPT Method", MDPI, Basel, Switzerland, Sustainability, 12(16), 6340; Sustainability, doi:10.3390/su12166340

Gender-inclusive Language

For the sake of easier readability, the present PhD thesis employs the usual masculine language form for personal nouns and pronouns. However, this does not imply any discrimination against the female gender, but should rather be understood as gender-neutral in the sense of linguistic simplification.

Lenguaje inclusivo de género

Para facilitar la lectura, la presente tesis doctoral emplea la forma usual de lenguaje masculino para los sustantivos y pronombres personales. Sin embargo, esto no implica ninguna discriminación contra el género femenino, sino que debe entenderse como neutral en cuanto al género en el sentido de simplificación lingüística.

Summary

Over the last century, the construction industry has achieved only slow progress in improving productivity and efficiency compared to other industries. This could not even be decisively improved by introducing and utilizing essential innovations in construction planning and project management or by increasing the reliability of schedules and costs. This trend was only slightly revised upwards by the technological innovations developed and introduced in the first two decades of the current century, aimed at optimizing the construction schedule and taking strategic measures to improve the operational organization of construction processes. Day-to-day practice in the construction industry has also revealed that significant difficulties still remain in meeting the planned execution deadlines and construction costs. This indicates that the multitude of existing successful methods for organizing scheduling, cost control, and construction planning, as well as for work execution management, are not being used to their full potential.

Furthermore, it appears that none of the approaches developed so far is capable of meeting the multifaceted demands and individual process requirements associated with each of the present construction project phases. A holistic concept that comprehensively optimizes the construction planning and processing organization and simultaneously guarantees schedule and cost reliability from the outset is currently still lacking. It is also urgently necessary to identify discrepancies between the planning and execution of construction by means of ongoing and explicit as-planned/as-built comparisons so as to produce a sustainable enhancement upon which to base the planning of future projects. Thus, this work represents one reliable method, that is capable to achieve significant and sustainable improvements in project outcomes in the future. Additionally, it could also significantly influence the overall productivity growth of the construction industry as a whole, particularly through significant increases in efficiency.

As the need to develop a concept, which addresses these requirements has become more urgent due to the above-mentioned explanations, the present paper first tries to work out, why the currently applied planning tools and even the latest agile project organization approaches have not yet developed their full potential. To this end, a comprehensive literature study and an in-depth construction process analysis were conducted, in which the varied and ongoing weaknesses and problems in the areas of construction planning and operational organization, as well as the management of deadlines and costs were identified.

On this basis, a comprehensive and coherent method for construction planning and execution organization was developed as an approach to solve the described problems. This solution's key process employs a building information model whereby—during the planning phase—the 3D model objects are closely linked to the corresponding scheduled activities and the associated construction cost items. The key data of a waterfall-based construction process simulation, calculated and defined during the project planning phase, provide essential benchmark parameters that subsequently form the framework for a multi-flexible project execution on the construction site. By implementing information feedback loops into the overall process, it is possible to continually perform target/actual comparisons based on the construction planning in conjunction with the respective construction statuses, thereby enabling continuous specification as a basis for future project planning.

In order to evaluate the new method's applicability and potential for optimization, a comparative case study was conducted with two real construction projects. Based on the results, a multi-criteria analysis was carried out, the results of which have shown a significant increasement of the project organization performance, as well as in reliability concerning deadlines and costs. Further studies on selected reference projects are required in order to validate these initial findings and to assess the method's applicability in light of an optimal project type and size.

Keywords: 5D building information modeling; 5D-PROMPT; Lean construction; schedule reliability

Resumen

En el último siglo, la industria de la construcción sólo ha logrado un lento progreso en la mejora de la productividad y la eficiencia en comparación con otras industrias. Esto no ha podido mejorarse decisivamente ni siquiera mediante la introducción y utilización de innovaciones esenciales en la planificación de la construcción y la gestión de los proyectos o incluso mediante el aumento de la confiabilidad de los cronogramas de obra y los costos. Esta tendencia ha sido ligeramente revisada después por las innovaciones tecnológicas desarrolladas e introducidas en las dos primeras décadas del siglo actual, destinadas a optimizar el cronograma de obra y a adoptar medidas estratégicas para mejorar la organización operacional de los procesos en los sitios de construcción. La práctica cotidiana en la industria de la construcción también ha revelado que siguen existiendo importantes dificultades para cumplir los plazos de ejecución y los costos de construcción previstos. Esto indica que la numerosa cantidad de métodos exitosos existentes para organizar la programación, el control de costos y la planificación de la construcción, así como para la gestión de la ejecución de las obras, no están siendo utilizados en todo su potencial.

Además, parece que ninguno de los enfoques desarrollados hasta ahora puede satisfacer las polifacéticas demandas y los requisitos de procesos individuales asociados con cada una de las fases del proyecto de construcción actuales. Todavía hace falta un concepto integral que optimice ampliamente la organización de la planificación y el proceso de construcción y que garantice simultáneamente la fiabilidad de los cronogramas y los costos desde el principio. También es necesario identificar urgentemente las discrepancias entre la planificación y la ejecución de la construcción mediante comparaciones continuas y explícitas entre lo planificado y lo construido realmente, a fin de producir una mejora sostenible en la cual poder basar la planificación de los proyectos futuros. Esto representa un método confiable para lograr mejoras significativas y sostenibles en los resultados de los proyectos en el futuro. Además, también podría influir significativamente en el crecimiento general de la productividad de la industria de la construcción en su conjunto, particularmente mediante aumentos significativos de la eficiencia.

Dado que la necesidad de elaborar un concepto que aborde estos requisitos se ha hecho más urgente debido a lo anterior, en el presente documento se intenta, en primer lugar, determinar por qué los instrumentos de planificación aplicados actualmente e incluso los últimos enfoques ágiles de organización de proyectos no han desarrollado aún todo su potencial. Con ese fin, se ha realizado un amplio estudio bibliográfico y un análisis a fondo del proceso de construcción, en el que se han identificado las diversas y continuas debilidades y problemas en las áreas de la organización de la planificación y operación de la construcción, así como en la gestión de los plazos y los costos.

Sobre esta base, se elaboró un método amplio y coherente para la organización de la planificación y el procesamiento de la construcción como un enfoque para resolver los problemas descritos. El proceso clave de esta solución emplea un modelo de información de la construcción en el que, durante la fase de planificación, los objetos del modelo 3D están estrechamente vinculados a las actividades programadas correspondientes y a las partidas de gastos de construcción asociadas. Los datos clave de una simulación "cascada" del proceso de construcción, calculados y definidos durante la fase de planificación del proyecto, proporcionan parámetros de referencia esenciales que posteriormente constituyen el marco para una ejecución ágil del proyecto en el sitio de la construcción. Mediante la aplicación de bucles de retroalimentación de información en el proceso global, es posible realizar continuamente comparaciones teórico/reales basadas en la planificación de la construcción en conjunción con el estado respectivo de la construcción, permitiendo así una especificación continua como base para la futura planificación del proyecto.

A fin de evaluar la aplicabilidad del nuevo método y su potencial de optimización, se realizó un estudio de caso comparativo con dos proyectos de construcción reales. Sobre la base de los resultados, se realizó un análisis multicriterio cuyos resultados demostraron un aumento significativo en el rendimiento de la organización del proyecto, así como de la fiabilidad en cuanto a plazos y costos. Es necesario realizar nuevos estudios sobre determinados proyectos de referencia a fin de validar estas conclusiones iniciales y evaluar la aplicabilidad del método a la luz de un tipo y tamaño de proyecto óptimos.

Palabras clave: 5D building information modeling; 5D-PROMPT; Lean construction; schedule reliability.

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Glossary

BU	Billing Unit
BIM	Building Information Modeling / Building Information Model
BMVI	(*Bundesministerium für Verkehr und Digitale Infrastruktur*) Federal Ministry of Transport and Digital Infrastructure
BoQ	Bill of Quantities
BU	Billing Unit
CAD	Computer-Aided Design
EU	European Union
GDP	Gross Domestic Product
HOAI	(*Verordnung über die Honorare für Architekten- und Ingenieurleistungen*) Regulation on remuneration for services provided by architects and engineers
IT	Information Technology
JiT	Just in Time
LM	Lean Management

LCM	Lean Construction Management
LoD	Level of Detail / Level of Geometry
LoI	Level of Information
LPS	Last Planner System
m2	Square meters
m3	Cubic meters
NBIMS	National Building Information Model Standard (US)
OECD	Organization for Economic Cooperation and Development
OU	Organization Unit
PROMPT	Process-Related Organization Maintains Project Timelines
PF	Project Frame
PS	Project Section
QTO	Quantity Takeoff
RU	Report Unit
SSOT	Single Source of Truth

ToS	Theory of Systems
TQM	Total Quality Management
TU	Task Unit
UoM	Unit(s) of Measurement
US	United States
VDI	(*Verein Deutscher Ingenieure*) Association of German Engineers
VSM	Value-Stream Mapping

Structure of the Dissertation

The present work assesses the problem of the repetitive extension of construction schedules and costs in the execution of construction projects. Initially, the primary reasons that contribute to the formulation of the research question are presented. Subsequently, based on a detailed literature investigation as well as an analysis of current project planning and organizational methods, significant causes of failure and potential for improvements regarding error-driven schedule management and cost control are evaluated. Based on these findings, a specific description of the problem statement is presented.

The hypothesis projects a clear and sustainable enhancement of the schedule and cost reliability and suggests a novel and inclusive construction planning and execution method, which utilizes a specifically composed set of previously established and successful construction planning and project management approaches as an overall solution.

The core of this work concerns the development and description of a new comprehensive construction planning and execution management method combining recently developed technologies for project planning with already proven and reliable project organization approaches. During the project design phase, a 5D building information model (5D BIM) is generated, whereby the schedule and cost-related elements are closely linked to the corresponding objects of a 3D BIM. Next, the 5D BIM's construction execution sequence is simulated in accordance to a waterfall-based project schedule in order to determine important project execution events, such as project start/end date and significant project milestones. Subsequently, these events are transferred to the project execution phase for application as a basic grid for a multi-flexible (agile) construction execution organization.

During and post multi-flexible construction, with frequent target/actual comparison, deviations between planned and actually required resources and effort values of the current construction project are constantly determined. Considerable findings are provided back to the planner`s stage in order to contribute to sustainable optimization and enhancement of future planning data.

The new method’s mechanism, applicability, and performance regarding the improvement of cost and schedule reliability during project realization were tested in a comparative case study and analyzed within a detailed multi-criteria analysis. In the following step, the results are evaluated and discussed with regard to current state approaches as well as the effects as a consequence of the implementation.

Finally, an outlook is provided concerning potential development options and research questions in order to improve the schedule and cost adherence of future construction projects.

As part of the mandatory requirements of the Escuela de Doctorado de la Universidad de Cantabria (EDUC) as well as the Programa de Doctorado en Ingeniería Civil (PDIC) - *Normativa de Gestión Académica de los Estudions de Doctorado - Real Decreto 99/2011* - it was part of the process of developing and writing the doctoral thesis, that essential parts and results of the work were published by one or more scientific articles. For this reason this work includes the contend of the following article:

"Leicht, D., Castro-Fresno, D., Dìaz, J., Baier, C., (2020), "Multidimensional Construction Planning and Agile Organized Project Execution - The 5D-PROMPT Method", MDPI, Basel, Switzerland, Sustainability, 12(16), 6340; Sustainability, doi:10.3390/su12166340"

Estructura de la Disertación

En el presente trabajo se evalúa el problema del exceso repetitivo de los plazos y los costos en la ejecución de los proyectos de construcción. Inicialmente, se presentan las razones principales que contribuyen a la formulación de la pregunta de la investigación. Posteriormente, basado en una investigación bibliográfica detallada, así como en un análisis de los métodos actuales de planificación y organización de proyectos, se evalúan las principales causas que llevan al fracaso y las posibilidades de mejora en lo que respecta a la gestión del cronograma y el control de los costos. Basado en estas conclusiones, se presenta una descripción específica del enunciado del problema.

La hipótesis proyecta una mejora clara y sostenible del cronograma y la confiabilidad de los costos y propone un método novedoso e inclusivo de planificación y ejecución de la construcción que utiliza un conjunto específicamente compuesto de enfoques de planificación y gestión de proyectos de construcción previamente establecidos y exitosos como solución general.

El núcleo de este trabajo se refiere a la elaboración y descripción de un nuevo método integral de planificación y ejecución de la construcción que combina tecnologías recientemente desarrolladas para la planificación de proyectos con enfoques de organización de proyectos ya probados y confiables. Durante la fase de diseño del proyecto, se genera un modelo de información de la construcción 5D (5D BIM), en el que los elementos de la planificación y de costos están estrechamente vinculados a los objetos correspondientes de un BIM 3D. A continuación, la secuencia de ejecución de la construcción del 5D BIM se simula en forma de “cascada” con un programa con el fin de determinar importantes eventos de ejecución del proyecto, como la fecha de inicio/fin del proyecto y los hitos importantes del proyecto. Posteriormente, estos eventos se transfieren a la fase de ejecución del proyecto para ser aplicados como una plantilla básica para una organización de ejecución de la construcción multiflexible (ágil).

Durante y después de la construcción ágil, con frecuentes comparaciones Teórico/reales, se determinan constantemente las desviaciones entre los recursos planificados y los realmente necesarios y los valores de esfuerzo del proyecto de construcción en proceso. Se proporcionan varias conclusiones considerables en la etapa de planificación a fin de contribuir a la optimización y mejora sostenibles de los datos de planificación futuros.

El mecanismo, la aplicabilidad y el rendimiento del nuevo método en lo que respecta a la mejora de la confiabilidad de los costos y cronograma durante la realización del proyecto se pusieron a prueba en un estudio comparativo de casos y se analizaron en el marco de un detallado análisis multicriterio. En la etapa siguiente, se evalúan y analizan los resultados con respecto a los enfoques del estado actual, así como los efectos como consecuencia de la aplicación.

Por último, se ofrece una perspectiva sobre las posibles opciones de desarrollo y preguntas de la investigación a fin de mejorar el cumplimiento de los plazos y los costos de los futuros proyectos de construcción.

Uno de los requisitos que recomienda la Escuela de Doctorado de la Universidad de Cantabria (EDUC) así como el Programa de Doctorado en Ingeniería Civil (PDIC), - *Normativa de Gestión Académica de los Estudions de Doctorado - Real Decreto 99/2011* - es que se publique al menos un artículo científico con algunos de los resultados obtenidos durante el proceso de desarrollo de la investigación asociada a la tesis doctoral. Es por ello que este trabajo incluye el contenido del siguiente artículo:

"Leicht, D., Castro-Fresno, D., Dìaz, J., Baier, C., (2020), "Multidimensional Construction Planning and Agile Organized Project Execution - The 5D-PROMPT Method", MDPI, Basel, Switzerland, Sustainability, 12(16), 6340; Sustainability, doi:10.3390/su12166340"

1. Background

As one of the oldest global sectors, the construction industry has undergone numerous change phases in addition to the integration of several new and innovative developments. Next to the workmanship in construction projects, the industrial prefabrication of construction components entered the sector. Additionally, building's technical equipment, as well as the size and complexity of projects, constantly increases. Furthermore, in the area of construction planning, far-reaching changes have been observed over the past decades. Next to computer-aided working methods to provide enhanced planning services, numerous strategic organization and management approaches have been implemented to realize current construction projects.

In this context, it could be expected that the construction industry has reached a high level in the areas of productivity, efficiency, planning, and execution quality, as well as cost and schedule adherence. But, the examination of the daily practice, exclusive of the specific statistical numbers and expert analysis, reveals a different picture. Both nationally and internationally, the timely completion of construction projects in private and public sectors, that meet the cost and schedule targets seems rather the exception than the rule. Considering the long history of the construction industry, this situation is difficult to understand.

Even latest technological and strategic developments, such as Building Information Modeling (BIM)-based construction planning, as well as agile organized project management, have only partially contributed to enhancements and standardization of planning and execution tasks. Additionally, the principles that were suggested through the optimization method of Lean Construction Management just offer limited stand-alone solutions. Nevertheless, they have considerably contributed to the enhancement of project execution organization, but do not provide sufficient potential for a coherent method that leads to a fundamentally improved status quo in the construction industry.

When it comes to implementation of innovative planning/management methods, new technologies or helpful software-supported tools in the construction sector, it is often argued - from a change management point of view - that each construction project must be considered as unique, which makes it impossible to compare one construction project to another (Tommelein 1998). However, with regard to the very high number of construction projects that are realized annually, it can be concluded that many of the services and processes performed are highly repetitive and stereotypes can be developed, which in turn can be standardized and optimized.

It can be observed that possible solutions developed and implemented in the construction sector so far can often be applied solely to a specific area within a construction project or to a specific phase of a project. Crucial information might be lost due to rigid interfaces (for example exchanges between different construction phases; use of different software tools, etc.). Moreover, a lack of information drawback`s from site back to the planning stage prevents the determination of "as-planned/as-built" deviations and thus sustainable refinements of the planning dataset cannot be achieved. The fact has yet been largely disregarded to conduct data collection of current and completed projects with consideration of significant deviations between the planning and execution data by continuously applied target/actual comparisons.

Due to the highlighted issues, which still prevail in the construction industry, and the current portfolio of possible solution approaches, it appears that a holistic and comprehensive solution strategy is not just "required", but absolutely crucial. In order to achieve this goal, the construction industry’s fundamental problems that affect productivity, efficiency, planning and implementation quality, as well as schedule/cost requirements need to be identified extensively. Furthermore, it needs to be deeply investigated why implemented methods, technologies, and software solutions are still lagging behind the attainable possibilities. For the development of a holistic solution, which takes into account a construction project`s process in general as well as each individual project phase, it is of particular importance to investigate its general and particular requirements. It is also essential to examine which information, dataset or processes must be interlinked, in order to gain a proper flow of the project as well as to prevent design, schedule and costs from drifting apart. Additionally, it is important to ensure that substantial information from the planning phase is transferred precisely into the construction phase and can be used accordingly. Findings of deviations between project design and execution of construction work must be determined and after evaluation reported back to the design stage, in order to gain continuously revised planning data, which can be used for future project planning.

This study seeks to develop a coherent method to implement the process outlined above. Furthermore, it aims to combine the strategies and technologies into one system as to provide aligned and optimized solutions for individual and specific weak points in today’s construction project structures.

1. Antecedentes

Como uno de los sectores más antiguo del mundo, la industria de la construcción ha pasado por numerosas fases de cambio, además de la integración de variados desarrollos innovadores. También, de la mano de obra en los proyectos de construcción, la prefabricación industrial de componentes de construcción entró en el sector. Adicionalmente, el personal técnico de los edificios, así como el tamaño y la complejidad de los proyectos, aumenta constantemente. Además, en el ámbito de la planificación de la construcción se han observado cambios de gran alcance en las últimas décadas. Además de los métodos de trabajo asistidos por computadora para prestar mejores servicios de planificación, se han aplicado numerosos enfoques estratégicos de organización y gestión para realizar los proyectos de construcción actuales.

En este contexto, se podría esperar que la industria de la construcción haya alcanzado un alto nivel en las áreas de productividad, eficiencia, planificación y calidad de la ejecución, así como de cumplimiento de los costos y plazos de ejecución. Pero el análisis de la práctica diaria, exclusivo de las cifras estadísticas específicas y el análisis de los expertos, revela un panorama diferente. Tanto en el ámbito nacional como en el internacional, la finalización a tiempo de proyectos de construcción en los sectores privado y público, que cumplen los objetivos de costos y tiempo, parece más bien la excepción que la regla. Teniendo en cuenta la larga historia de la industria de la construcción, esta situación es difícil de entender.

Incluso los últimos adelantos tecnológicos y estratégicos, como la planificación de la construcción basada en el modelo de información para la construcción (BIM por sus siglas en inglés), así como la gestión de la organización ágil de proyectos, sólo han constituido una contribución parcial a la hora de mejorar y estandarizar las tareas de planificación y ejecución. Además, los principios que se sugirieron mediante el método de optimización de la gestión de la construcción *lean* sólo ofrecen soluciones independientes limitadas. No obstante, han contribuido considerablemente a mejorar la organización de la ejecución de proyectos, pero no ofrecen un potencial suficiente para un método coherente que conduzca a un *status quo* fundamentalmente mejorado en la industria de la construcción.

Cuando se trata de aplicar métodos innovadores de planificación/gestión, nuevas tecnologías o instrumentos informáticos útiles en el sector de la construcción, se suele argumentar, desde el punto de vista de la gestión del cambio, que cada proyecto de construcción debe considerarse único, lo que hace imposible comparar un proyecto de construcción con otro (Tommelein 1998). Sin embargo, en relación con el muy alto número de proyectos de construcción que se realizan anualmente, se puede concluir que muchos de los servicios y procesos realizados son altamente repetitivos y esto puede generar tipologías, las cuales pueden estandarizarse y optimizarse.

Se puede observar que las posibles soluciones desarrolladas y aplicadas hasta ahora en el sector de la construcción a menudo pueden aplicarse únicamente a una zona específica dentro de un proyecto de construcción o a una fase específica de un proyecto. Se puede perder información crucial debido a la rigidez de las interfaces (por ejemplo, los intercambios entre las diferentes fases de la construcción, el uso de diferentes herramientas de software, etc.). Además, la falta de reportar la información desde el sitio de la construcción de regreso a la etapa de planificación impide la determinación de desviaciones "según lo previsto/construido" y, por lo tanto, no puede lograrse un perfeccionamiento sostenible del conjunto de datos de planificación. Se ha hecho caso omiso en gran medida de este hecho en el momento de llevar a cabo la recolección de datos de proyectos en curso y terminados teniendo en cuenta desviaciones significativas entre los datos de planificación y ejecución mediante comparaciones teórico/reales aplicadas continuamente.

Debido a las cuestiones destacadas, que siguen prevaleciendo en la industria de la construcción, y a la cartera de posibles enfoques de solución, parece que una estrategia de solución integral y completa no sólo es "necesaria", sino absolutamente crucial. A fin de lograr este objetivo, es necesario identificar extensivamente los problemas fundamentales de la industria de la construcción que afectan a la productividad, eficiencia, calidad de la planificación y ejecución, y los requisitos de cronograma/costos. Además, es necesario investigar a fondo por qué los métodos, tecnologías y soluciones de software implementados siguen quedando por detrás de las posibilidades asequibles. Para el desarrollo de una solución integral, que tenga en cuenta el proceso de un proyecto de construcción en general así como cada fase individual del proyecto, es de particular importancia investigar sus requisitos generales y particulares. También es esencial examinar qué información, conjunto de datos o procesos deben estar interrelacionados, a fin de obtener un flujo adecuado del proyecto, así como para prevenir que el diseño, el calendario y los costos se desvíen. Adicionalmente, es importante asegurar que la información sustancial de la fase de planificación se transfiera con gran precisión a la fase de construcción y pueda utilizarse en consecuencia. Las desviaciones entre el diseño del proyecto y la ejecución de la construcción deben determinarse y, tras la evaluación reportarse de regreso a la etapa de diseño, a fin de obtener datos de planificación continuamente revisados, que puedan utilizarse para la planificación de futuros proyectos.

El presente estudio trata de desarrollar un método coherente para llevar a cabo el proceso descrito anteriormente. Además, pretende combinar las estrategias y tecnologías en un sistema para proporcionar soluciones alineadas y optimizadas para los puntos débiles, tanto individuales como específicos, de las estructuras de los proyectos de construcción actuales.

2. Introduction

2.1. The Construction Productivity Issue

The construction industry is of particular importance for international economic conditions, having provided approximately 5.4%[2] of the European and 4.0%[3] of the US gross domestic product (GDP) in 2017[4]. In addition, it essentially affects an extensive range of further economic branches (European-Commission 2017, U.S.-Bureau-of-Economic-Analysis 2017). Moreover, it represents a key factor for the definition of the EU's 2020 goals, among others, in smart and sustainable progression (European-Commission 2017, Hanna and Iskandar 2017).

Compared to other industrial sectors, throughout the first part of the last century, the building industry lagged far behind in its development and implementation of advanced technological achievements. While numerous other industries quickly began adopting various innovations, technical improvements, and management strategies, the construction sector has nearly missed pursuing this trend. Historically, this sector instead followed a conservative approach in implementing structures for progressive management, design, and delivery, excused by arguments of single-piece production, craftsman manufacture, and adjustments due to continuously changing customer requirements (Dave, Kubler et al. 2016, Jin, Hancock et al. 2017).

During the latter half of the last century, an increasing number of construction projects has struggled with an ever-expanding system of complex and multi-faceted planning and execution specifications, constantly affected by differing motivations between various project participants and also frequently subjected to a large number of supply chain connections (Oppong, Chan et al. 2017). Moreover, tight time and budget constraints and rising technical challenges have created tough conditions for keeping projects within the envisaged timeframes (Oesterreich and

[2] Gross value added at basic prices 2017; percent share of total gross value added.

[3] Value added as a percentage of gross domestic product (%).

[4] At the time of the investigation the values of 2018 were not yet available.

Teuteberg 2016). Insufficient limitations for design changes in late project stages due to changing customer requests have further increased the risk of postponements and temporal issues. Applied schedule methods have often failed to meet the project-specific process requirements. Furthermore, it became difficult to prevent increasing project costs, and therefore, project failure became predictable (Buvik and Tvedt 2017, Kim and Nguyen 2018). Aching effects of this development aimed in significant project time and budget overruns, which negatively affect construction project outcomes and, not least of which, result in customer dissatisfaction. Ballard stated in 1993 the average value of engineering deliverables that were behind schedule exceeded the 30% mark (Ballard 1993). This assertion was underpinned by Flyvbjerg et al. in 2002, who summarized the average cost-overrun factor of construction projects from the last 70 years, which had an average value of 28% (Flyvbjerg, Holm et al. 2002).

This trend heavily influences the global construction productivity growth, verifiable by the international productivity ratings recorded by different international statistic institutions. Generally, these values were documented within a monthly, quarterly, or annual sequence in order to gain and provide reliable data concerning the national or worldwide economic growth of a specific industry or region. Therefore, to obtain a comprehensive reasoning behind the aforementioned circumstances and to allocate possible causes, a closer look at the productivity growth of the construction sector is of particular importance. Furthermore, comparing these values against other industries and regions may provide additional conclusive information regarding the construction industry's general situation (Ballard 2000, Publications-Office-of-the-European-Union 2003).

However, given that crucial international institutions only began collecting data about the economic development throughout the latter half of the previous century, conclusive verification of this trend has been difficult to trace. The relevant literature and national or international statistic institutions rarely possess and provide valid information. In 2001, Teicholz conducted an examination of US construction labor productivity trends between 1970 and 1998, identifying significant hurdles in comparing industry and project-related productivity values due to deviating factors and different activity segments under consideration (Teicholz, Goodrum et al. 2001). Moreover, deflators and exchange factors further contributed to these unreliable results.

This situation made it necessary to ascertain miscellaneous breakdown values in order to make the construction sector's productivity comparable to other industry branches. Therefore, to compare the construction industry conditions against those of other branches of industry, single segments and individual recourse values (e.g., annual labor productivity) had to be evaluated and compared in a separated manner (Teicholz, Goodrum et al. 2001, Vogl and Abdel-Wahab 2015). For the purpose of this analysis, the ratings of annual labor productivity[5] were considered, as they provided the most likely information regarding global conditions at that time. The annual labor productivity is calculated by the ratio of the annual GDP and the aggregated annual working hours (Teicholz 2001, O`Mahony and Van Ark 2003, Publications-Office-of-the-European-Union 2003). Concerning the growth of the annual labor productivity, in 2003, the European Communities published the growth of 15 European member states[6] (hereinafter referred to as EU-15) as well as the United States (US), gathered between the years 1979 and 2001 and separately summarized for 1979–91, 1991–95, and 1995–2001 (see Figure 1 and Figure 2; Publications-Office-of-the-European-Union 2003).

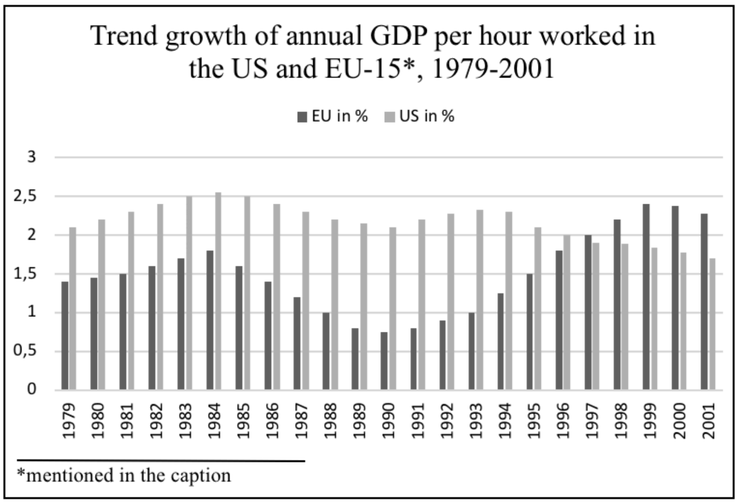


Figure 1: Trend growth of the annual gross domestic product (GDP) per hour worked – Comparison between the EU-15[6] and US markets during the years 1979–2001 (based on Publications-Office-of-the-European-Union 2003)

[5] Annual labor productivity growth is defined as the growth (value added) at constant prices minus the growth in hours worked. This section looks at labor productivity growth contrasting the EU-15[6] and US over the period of 1979-2001 at the level of 56 industries. The base calculations (reference values) employ GDP figures, deflated by US price indices for the ICT industries (NACE 30-33).

[6] List of countries considered in the database: Belgium, Luxembourg, Denmark, Germany (West Germany – 1979-91; United Germany – 1991-2001), Greece, Spain, France, Ireland, Italy, Netherlands, Austria, Portugal, Finland, Sweden, United Kingdom.

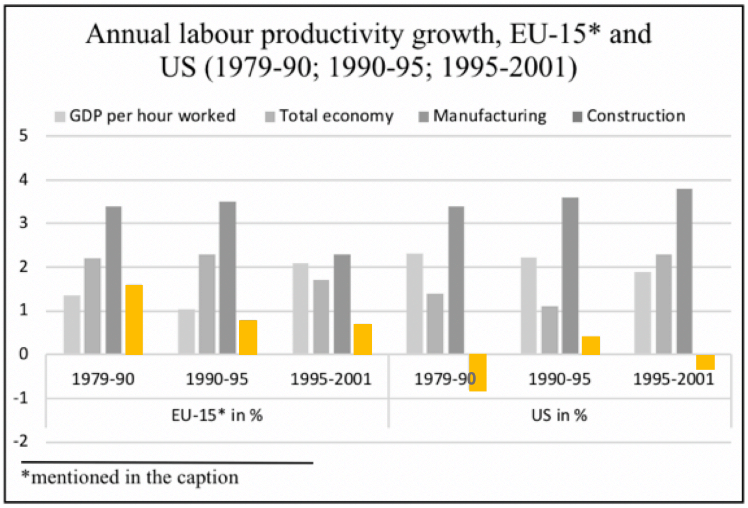


Figure 2: Annual labor productivity[5] growth of the total economy, the manufacturing industry, and the construction sector – Comparison between the EU-15[6] and US markets during the years 1979–90, 1990–95, and 1995–2001 (based on Publications-Office-of-the-European-Union 2003)

Figure 1 presents the course of the GDP per hour worked in the EU-15[6] and US between the years 1979 and 2001. This illustrates the EU values were consistently much lower than those of the US. It continued until roughly 1997, after which the US curve flattens out to some degree while the EU values rise considerably. Figure 2 demonstrates the cumulated average value of the European annual labor productivity of all economic sectors (presented as Total economy) has slowly declined from 2.2% to 1.7% while the US value has grown—after an initial downturn—from 1.4% to 2.3% between 1979 and 2001. Concerning the development of the construction industry, the graph illustrates a slight decrease of the European values from 1.6% to 0.7% while the US course started at −0.8%, recovered to 0.4%, and dropped down again to −0.3% (Teicholz, Goodrum et al. 2001, Publications-Office-of-the-European-Union 2003, Hanna and Iskandar 2017).

These results alone would not indicate exceptional progress. Of particular importance is the considerable deviation between the values of the construction and manufacturing industries. In the EU, the course of the manufacturing industry began at 3.4% and dropped to 2.3% while the US value increased from 3.4% up to 3.8% in this time period. As such, the average deviation of the annual labor productivity between the manufacturing and construction industries reached approximately 2.0% in Europe and 3.8% in the US (Teicholz, Goodrum et al. 2001, Hanna and Iskandar 2017).

The graphs presented above offer a general explanation of the situation faced by the construction industry in the EU-15[6] and the US throughout the last phase of the previous century, which points to fundamental weaknesses in the construction industry compared to the production industry. If it is now assumed, as described previously, that annual labor productivity is calculated by the ratio of the annual GDP and aggregated annual working hours, this indicates extremely inefficient working practices in the construction industry. The reasons for this are consequently a result of the general way the construction industry has dealt with increasingly complex requirements and new challenges in the areas of construction planning, project management, and work execution. These findings also possess special significance for understanding the specific root causes that have prevailed in the construction industry until today.

2.2. Stagnating Growth despite further Innovations

Nevertheless, important technological and strategic innovations were also applied in the construction industry towards the second half of the previous century and then increasingly pursued in the first two decades of the current one, triggered by the common innovation trends during this period of time. Traditional project planning methods and former manually executed management operations were transferred to digitalized planning (design) and IT-based cost and time management applications. As a result, two-dimensional (2D) computer-aided design (CAD) became a widespread standard for project design tasks, and it has remained until today.

To grasp a project's time course, certain scheduling tools, largely transmitted from other industry branches, have been established to simplify project management activities (Waly and Thabet 2003, Tomek and Kalinichuk 2015). This transition was simultaneously accompanied by the initial development of productivity improvement and quality management initiatives (e.g., lean management and total quality management [TQM]), which were adopted from the automotive industry and implemented in the construction sector since the 1980s (Ballard 2000, Sacks, Eastman et al. 2004, Tanyer and Aouad 2005, Sacks, Radosavljevic et al. 2010). Utilization of the lean principles resulted in workflow-oriented process structures, which were established in construction projects and should contribute to streamlining planning, execution, and management activities (Sacks, Koskela et al. 2010).

The common and so far only possible planning method based on paper plans, such as physical 2D drawings and handwritten documents, has mostly been changed towards 2D CAD (Goedert and Meadati 2008). Today, CAD planning has become a mandatory aspect and major factor for quality and success in the overall construction sector. As a result, further IT applications were implemented in order to benefit from this promising progression (Meeran and Pratt 1993). Additionally, it was found that digital soft- and hardware applications could be implemented for project cost and time management tasks (Waly and Thabet 2003). Further technological and strategic progression in the construction sector produced new advancements in the field of IT-based applications and management methodologies, and thus further development got 3D CAD planning off the ground (Goedert and Meadati 2008).

Developed based on the 2D CAD technique, 3D CAD planning involves generating a three-dimensional project model as a composite of individual model objects. Beyond the geometrical design, the model also contains numeric information regarding the specific object dimensions (e.g., length, width, height, area, volume, etc.).

Computer-based modelling of construction projects, developed by parametric 3D CAD systems, has quickly provided numerous benefits for increasing construction productivity values as, for instance, rapid creation of different design variations and project alternatives, which became easier to achieve. Furthermore, previous planning outputs could be proceeded, which offered the advantage that drawings and plans did not have to be redrawn from scratch, but could instead be developed further with a smaller scale of the Level of Detail / Level of Geometry (LoD) and an even deeper level of information (LoI). A considerable advantage was also identified in the simplified correction of errors, since the drawings or models could be corrected without the common requirements of physical treatment (erasing or scraping off the top layer of the paper), and thus did not require to be redrawn. Moreover, a barely realistic illustration of the future building became possible by the provided rendering features, which has today become common practice (Waly and Thabet 2003, Sacks, Eastman et al. 2004).

The development of 3D CAD technology has subsequently provided the foundation for the innovation of BIM, developed since the last third of the 20th century.

The following basic characteristics have been considered for Building Information Modeling:

- A BIM features geometrical, numerical, and alphanumerical information.
- A BIM is composed of the individual model objects and elements.
- The characteristic information of each model object is contained within the corresponding model attributes.
- Both geometrical as well as alphanumerical information can be retrieved from the model.
- The model information can be stored in databases and exchanged between individual project participants, enabling cooperation activities and providing the basis for a single source of truth (SSOT).

The German Federal Ministry of Transport and Digital Infrastructure (Bundesministerium für Verkehr und Digitale Infrastruktur [BMVI]) describes BIM as follows: "*Building Information Modelling refers to a cooperative working methodology, based on digital models of a building structure, to consistently record and manage life-cycle relevant information/data for transparent communication and exchange between stakeholders or to pass it over for further procession*" (BMVI 2015). A similar explanation was provided by the US National Building Information Model Standard (NBIMS), were BIM was described as "*a digital representation of physical and functional characteristics of a facility, and it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle from inception onward*" (Campbell and Acm 2007).

Beyond geometry parameters, BIM also contains crucial attributes about project-concerned 3D BIM objects, which can be changed, modified, and updated by authorized project members (Goedert and Meadati 2008). Captured information can also be stored and managed via databases, keeping the data available and manageable for exchange or reuse. The 3D BIM model further represents the building project as an illustration of the database content (Autodesk 2002). As such, BIM applications should increase work quality, accelerate productivity, and improve long-term project results while costs for project stakeholders should be reduced and project durations shortened. Furthermore, BIM could be utilized for project, data and information management according to customer requirements (Dìaz and Silbe 2017). Users also benefit from system features, which help to organize specific project data according to sections, rooms, or even single components and to create efficient long-term data availability (Autodesk 2002, King 2017).

Since the development and implementation of BIM in the construction sector, this industry has been increasingly determined by a digital and BIM revolution. Examining the international trend regarding BIM applications reveals significant implementation incensements, especially in the US, Great Britain, Eastern Asia, the Scandinavian region, Germany, and a number of other countries. To gradually establish BIM in Germany, in 2015, the BMVI introduced a step-plan called "*digital design and construction*"[7] (Koo and Fischer 2000, BMVI 2015). Its primary purpose is to transform current design and construction methods towards digitalization and to

[7] The step-plan has been developed by the „planen-bauen 4.0 - Gesellschaft zur Digitalisierung des Planens, Bauens und Betreibens mbH“ under the authority of the BMVI.

establish BIM as the new standard for public infrastructure projects; moreover, digital planning and construction methods should be established as a nationwide standard for public construction projects until 2020. The German institution "*planen-bauen 4.0*" facilitates the central principle, whereupon the “*practical construction execution*” can only start when the “*digital construction process*” has been completed. This statement clarifies the future requirements of the building sector and defines the challenges that participants of the construction value chain must adjust to in the future (Koo and Fischer 2000, Autodesk 2002, BMVI 2015).

To achieve a sophisticated and proven solution for project design tasks, it became an obious solution to combine the previous methods. Therefore, beyond the 3D BIM model, the entire project design targets—including time (4D) and costs (5D)—must be considered. This innovation evolved into the development of the 4D and 5D concept, whereupon project design is closely connected to project cost and execution duration values (Fan et al. 2015; Sánchez-Rivera et al. 2017; Fischer and Aalami 1996). Synergizing the BIM and 5D approaches resulted in the BIM 5D methodology, which additionally provides the possibility of virtual construction sequence simulation based on the 3D BIM model and the corresponding project cost and schedule information (Fischer et al. 1996; Koo et al. 2000; VDI, 2018).

In 1996, Fischer et al. investigated and described the enhancement of 4D construction design and management (Fischer et al. 1996; Koo et al. 2000). The 4D planning method consists of 3D CAD model design combined with time and scheduling aspects. The basic idea is to tie the progress of the schedule or even single dates (e.g., project start/end date; milestones and deadlines; etc.) closely together with the corresponding 3D project model objects in order to achieve a transparent and manageable project development and work execution scenario (Fischer et al. 1996; Koo et al. 2000). Regarding schedule-clash identification and interference analysis, the 4D model approach turned out to be optimally applicable, as Koo et al. demonstrated in their investigation published in 2000 (Koo and Fischer 2000).

Furthermore, site management has been significantly improved by implementing the 4D method, as stated by Chau et al. in 2004 (Koo and Fischer 2000, Chau, Anson et al. 2004). These proceedings and verifiable improvements have also contributed to include a further dimension, which consequently resulted in the previously mentioned 5D[8] planning approach. This method is characterized by a 3D BIM or CAD model of the concerned project (3D); the time aspect for a virtual and realistic project schedule planning (4D); and the corresponding cost factors to present the project cost development in relation to the allocated execution activities (5D). Pursuant to the project proceeding, in accordance with the 3D model requirements and planned project timeline, the cost or schedule chart could display current provisional project cost values at each point in time throughout the virtual project planning. From this, a largely clear and comprehensible project status overview has become achievable (Tanyer and Aouad 2005, Kuenzel, Teizer et al. 2016, European-Commission 2017). The demand for a correlation between planning, cost, and scheduling issues has thus become a major requirement for preventing project design as well as corresponding costs and schedule activities from drifting apart.

In the past, numerous different IT-based schedule solutions have been developed and implemented within the construction sector; though not initially appropriate for 5D applications, they have been increasingly used in this manner. These scheduling tools are largely based on the waterfall principle (Echeverry et al. 1991; Tory et al. 2013). This principle follows a strictly hierarchical embossed structure based, in general, on the ratio between chronological task orders and execution dates or duration. Its greatest advantage concerns in its high planning reliability, which is mandatory for large-scale project management (Tomek et al. 2015). Due to the regular organization, this method is ideally suited for projects with consistently proceeding requirements and long-term recognizable interventions (Echeverry et al. 1991). Fast-track changing procedures and ad-hoc operations obstruct this progress. Most common examples of waterfall-based applications include the Gantt Chart, line of balance, or the critical pass method (Tory et al. 2013).

[8] Further approaches, like sustainability (6D) and facility management (7D) approaches have recently been developed, but should not be taken into further account in order to keep the scope of the present thesis within reasonable boundaries. See the following souces: (Redmond, A., Hore, A., Alshawi, M., and West, R., (2012) "Exploring how information exchanges can be enhanced through Cloud BIM." Automation in Construction 24: 175-183; Fan, S. L., Wu, C. H., and Hun, C. C., (2015) "Integration of cost and schedule using BIM." Journal of Applied Science and Engineering 18(3): 223-232; Sánchez-Rivera, O. G., Galvis-Guerra, J.A., Porras-Díaz, H., Ardila-Chacón, Y.D., Martínez-Martínez, C.A. (2017) "BrIM 5D models and Lean Construction for planning work activities in reinforced concrete bridges" Tunja-Boyacá, Colombia, Revista Facultad de Ingeniería. 26: 39-50.).

Another revolutionary attainment was achieved by transforming and implementing the lean approach within the construction sector. Originally invented by Taiichi Ohno—a production engineer at the Toyota Motor Company—the general principles of lean were classified into five main points, the "Lean principles" by James P. Womack, Daniel T. Jones, and Daniel Roos (Womack 1990, Womack and Jones 2003). The following graphic represents an overview of the five basic lean principles, and moreover, it provides individual implementation examples (Figure 3):

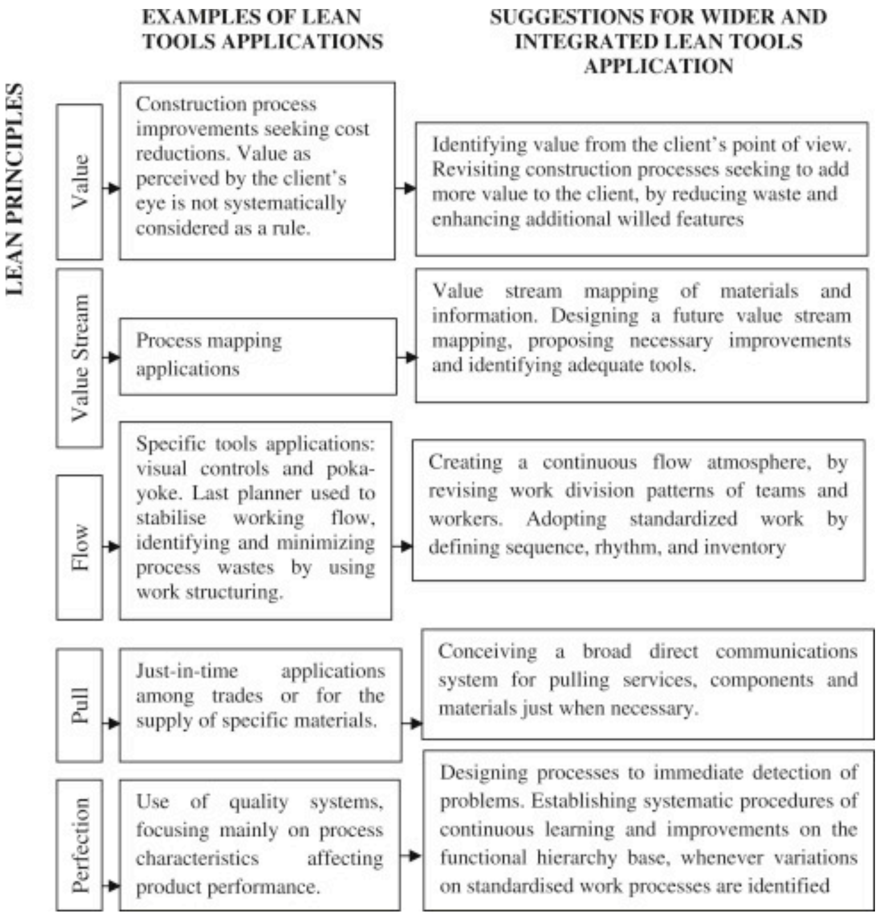


Figure 3[9]: The five Lean principles (Oladapo, Oginbiri et al. 2019)

The focus of lean is to increase customers value via total elimination of any kind of waste and by optimizing the overall value stream, including all corresponding or influencing factors (Womack 1990, Womack and Jones 2003). Due to its considerable success, the lean principles were

[9] This figure was provided by the article "Oladapo, A. A., O. Oginbiri and J. S. Goulding (2019). Lean Principles in construction (Chapter 12)." Elsevier - with friendly permission from Elsevier.

transferred and implemented to the construction industry throughout the last two decades. According to the Association of German Engineers (VDI) regulations (VDI 2553), lean construction describes the transformation of the lean management approach as a comprehensive production system for use in construction planning and execution tasks, including all participant processes as well as cooperation with each involved stakeholder. Timeliness, cost compliance, transparency, process and work-execution quality, and performance values represent the key factors for achieving cross-company project success. Moreover, the objective of lean construction focuses on stabilization, optimization, and acceleration of construction process workflows as well as material and information logistics (VDI 2017).

A significant output of the lean philosophy was the development of the last planner system (LPS) around the turn of the millennium. The LPS pursues significant improvements regarding project execution, site management, and execution schedule reliability. The core concept consists of a team-based project task organization that incorporates foremen's and site manager's practical experience and utilizes a flexible structured strategy for the execution order of the construction trades (Ballard 2000, Howell, Ballard et al. 2004).

Making progress towards this goal, Ballard introduced the initial "Last Planner" approach in 1993, which was substantially influenced by the Toyota Production System and the production theory of Lauri Koskela (Ballard 1993, Ćwik and Rosłon 2017). This approach was developed further and finally presented by Ballard in 2000 as the LPS for use in managing construction execution activities (Ballard 2000, Hamzeh, Saab et al. 2015; see Figure 4):

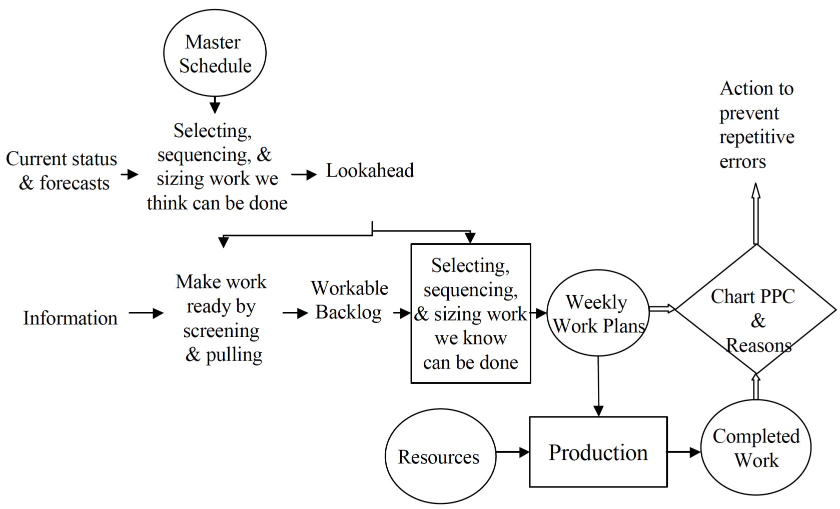


Figure 4: Last planner system (LPS) with look-ahead process highlighted (Ballard 2000)

The LPS is generally based on the crucial lean principles of waste reduction, pull-planning, value-stream mapping (VSM), and just-in-time (JIT) delivery. Furthermore, the LPS is used to plan, monitor, and control construction execution processes. In early steps, specific attention is placed on development and utilization of weekly work plans, devised by project managers and foremen in the key role of the last planner. Following this, look-ahead plans for controlling and maintaining the workflows are established. The focus thus shifted from productivity improvement to improving workflow reliability (Ballard 2000, Ballard and Howell 2003, Shang and Pheng 2014).

Moreover, the LPS is based on the agile methodology, which follows a maximum flexible mode of action. Its basic characteristic is that projects are developed step by step by interdisciplinary and decentral organized teams according to consecutive "sprints" (Owen et al. 2006). The purpose is to streamline project management efforts and to keep high flexibility even for changes in late project stages in order to rapidly meet customer requirements or to execute ad-hoc activities. Deficiencies of agile methods can be found in the lack of transparency of open task values. Furthermore, current agile methods are not yet customized and transformed into reasonable IT-based applications to be used accordingly in the construction sector (Ballard, 2000; Ballard et al. 2003).

The primary objective of the LPS is to endorse conversation and collaboration between foremen and project managers and to improve trust-based relationships within project team environments at different project levels by making upcoming issues visible for clarification before they escalate. Implementing the LPS contributes to increasing the possibility of reliable planning procedures and process workflows in addition to demonstrating that personal relationships and peer pressure may influence this process (Hamzeh, Saab et al. 2015, LCI 2015). In 2015, Mossman summarized eight exemplary reasons why the LPS is valuable for implementation in construction projects (Mossman 2015):

- Project duration will be reduced.
- Costs should be managed better.
- Project delivery will become safer.
- Stress on project/site managers will be reduced.
- Production programs should become more predictable.

- The overall production processes will be improved.
- Project schedules become reliable and JIT delivery is enabled.
- The critical path approach becomes redundant.

The LPS focuses on undisturbed construction execution processes, whereupon foremen and, in some instances, blue-collar workers are encouraged to work out detailed plans for upcoming tasks on site. These plans are reviewed before the work on site is executed. Moreover, expected or impending issues and constraints are removed in collaborative teamwork sessions. Promises made to each other within the team meetings are verified in terms of timely aspects and, moreover, are proofed against ambiguity. If permitted by the team, these promises are transferred into milestones and added to the work execution schedule, and thereafter, it becomes absolutely mandatory for the person or team responsible to implement the tasks properly and on time (LCI 2015, Russell, Liu et al. 2015).

Considering these achievements, a strong increase in the productivity values within the first two decades of the current century could reasonably be expected. However, the progress of the productivity graph took a rather different course, as illustrated by Figure 5 and Figure 6:

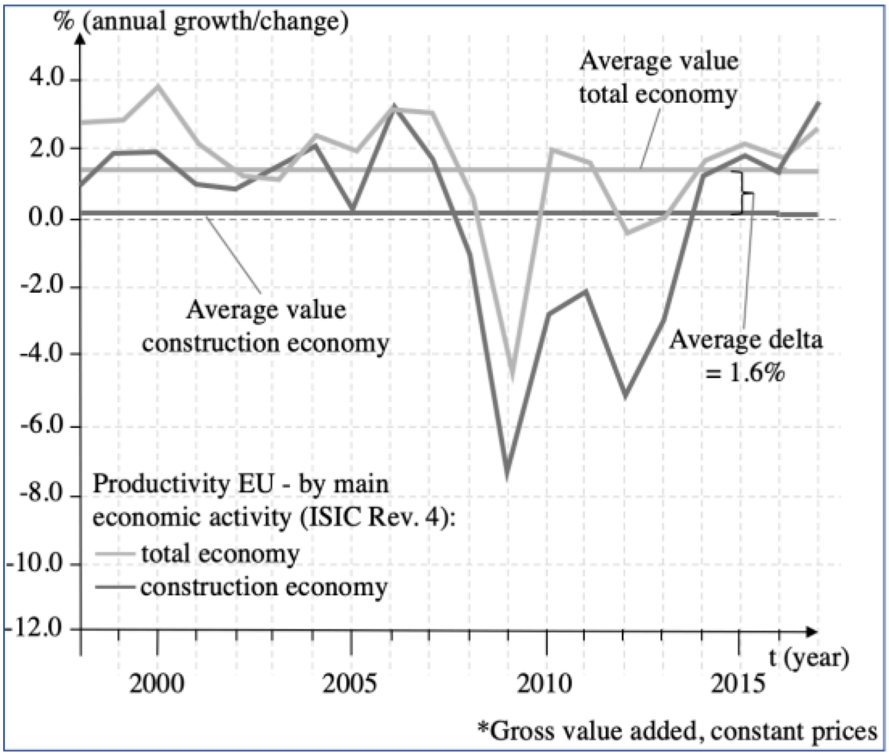


Figure 5: Annual productivity ratings of the EU; total economy vs. construction economy; Figure based on (OECD 2020)

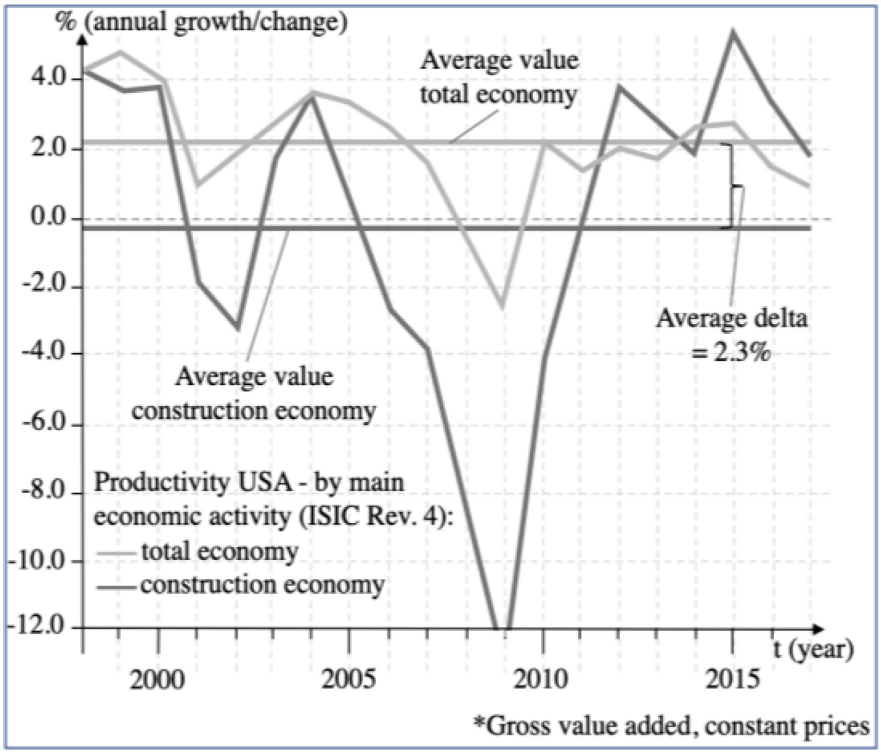


Figure 6: Annual productivity ratings of the US; total economy vs. construction economy; Figure based on (OECD 2020)

In order to demonstrate the continuing progress of the slowly increasing enhancements, which have still predominated in the construction sector, the productivity ratings (gross value added at constant prices) of 1995–2017 are represented above. These values were continuously recorded within this time period by the statistics department of the Organization for Economic Cooperation and Development (OECD); *comparable EU/US data are provided by the OECD only between 1995 and 2017* (OECD 2020). During this time, the average annual productivity growth of the European construction sector was at 0.1% while the average U.S. value equaled −0.2%. Compared to the total economy, these values indicate an average deviation of 1.6% in the EU and 2.3% in the US. Additionally the annual productivity values of the US construction sector increased between 2012 and 2019, highlighting the responsible factors for the error-triggering liabilities in the construction industry (OECD 2020).

Despite this large number of significant innovations and strategic improvements implemented within the construction industry over the past several years, as the presented graphs indicate, no considerable change in productivity enhancement has yet been achieved in this industry sector. As this result is difficult to comprehend, an intensive investigation of the possible causes is necessary. To this end, previously conducted research and provided literature should be investigated in order to determine the fundamental causes for this development. Moreover, currently applied project planning, management, and execution approaches have to be analyzed in the same context.

2. Introducción

2.1. El problema de la productividad en la construcción

La industria de la construcción es de particular importancia para las condiciones económicas internacionales, habiendo proporcionado aproximadamente el 5,4%[10] del producto interno bruto (PIB) europeo y el 4,0%[11] del estadounidense en 2017[12]. También afecta esencialmente a una amplia gama de otras ramas económicas (Comisión Europea 2017, Oficina de Análisis Económico de los Estados Unidos 2017). Además, representó un factor clave para la definición de los objetivos de la UE para el 2020, entre otros, en una evolución inteligente y sostenible (Comisión Europea 2017, Hanna y Iskandar 2017).

En comparación con otros sectores industriales, a lo largo de la primera parte del siglo pasado, la industria de la construcción se quedó muy atrás en el desarrollo y la aplicación de logros tecnológicos avanzados. Mientras que numerosas industrias comenzaron rápidamente a adoptar diversas innovaciones, mejoras técnicas y estrategias de gestión, el sector de la construcción no ha logrado seguir esta tendencia. Históricamente, este sector ha mantenido un enfoque conservador en la aplicación de estructuras para la gestión, el diseño y la entrega progresivos, excusándose en los argumentos de la producción de un solo elemento, la fabricación artesanal o manual y los ajustes debidos a los continuos cambios de las necesidades de los clientes (Dave, Kubler et al. 2016, Jin, Hancock et al. 2017).

Durante la segunda mitad del siglo pasado, un número cada vez mayor de proyectos de construcción se ha enfrentado a un sistema cada vez más amplio de especificaciones complejas y polifacéticas de planificación y ejecución, afectado constantemente por diferentes motivos entre los diversos participantes en el proyecto y también frecuentemente sometido a un gran número

[10] Valor añadido bruto a precios básicos 2017; porcentaje del valor añadido bruto total.

[11] Valor añadido como porcentaje del producto interno bruto (%).

[12] En el momento de la investigación los valores de 2018 no estaban todavía disponibles.

de conexiones de la cadena de suministro (Oppong, Chan et al. 2017). Además, las limitaciones de tiempo y presupuesto y los crecientes desafíos técnicos han creado condiciones difíciles para mantener los proyectos dentro de los plazos previstos (Oesterreich y Teuteberg 2016). Las limitaciones insuficientes para los cambios de diseño en las últimas etapas de los proyectos debido a las solicitudes de cambios de los clientes han aumentado aún más el riesgo de aplazamientos y problemas temporales. Los métodos de programación aplicados a menudo no han cumplido los requisitos de los procesos específicos del proyecto. Además, se ha vuelto difícil evitar el aumento de los costos del proyecto y, por lo tanto, el fracaso del proyecto se ha vuelto previsible (Buvik y Tvedt 2017, Kim y Nguyen 2018).

Los efectos de esta evolución se tradujeron en importantes aumentos de los plazos de ejecución y el presupuesto de los proyectos, que afectaron negativamente a los resultados de los proyectos de construcción y, no menos importante, provocaron la insatisfacción de los clientes. Ballard declaró en 1993 que el valor promedio de los entregables de ingeniería que estaban atrasados superaba la marca del 30% (Ballard 1993). Esta afirmación fue respaldada por Flyvbjerg et al. en 2002, que resumieron el factor promedio del aumento de los costes de los proyectos de construcción de los últimos 70 años, que fue del 28% (Flyvbjerg y Holm et al. 2002).

Esta tendencia influye en gran medida en el crecimiento de la productividad de la construcción a nivel mundial, lo que se puede verificar por las clasificaciones internacionales de la productividad registradas por diferentes instituciones internacionales de estadística. Por lo general, esos valores se documentan en una secuencia mensual, trimestral o anual a fin de obtener y proporcionar datos fiables sobre el crecimiento económico nacional o mundial de una industria o región específica. Por lo tanto, para obtener un razonamiento exhaustivo de las circunstancias antes mencionadas y asignar posibles causas, es de particular importancia examinar más de cerca el crecimiento de la productividad del sector de la construcción. Además, la comparación de esos valores con los de otras industrias y regiones puede proporcionar información adicional concluyente sobre la situación general del sector de la construcción (Ballard 2000, Publicaciones-Oficina de la Unión Europea 2003).

Sin embargo, dado que instituciones internacionales clave sólo comenzaron a reunir datos sobre el desarrollo económico durante la segunda mitad del siglo XX, ha sido difícil rastrear una verificación concluyente de esta tendencia. La bibliografía relevante y las instituciones de estadística nacionales o internacionales rara vez poseen y proporcionan información válida. En 2001, Teicholz llevó a cabo una evaluación de las tendencias de la productividad de la mano de obra de la construcción en los Estados Unidos entre 1970 y 1998, identificando importantes obstáculos para comparar los valores de productividad de la industria y de los proyectos. Esto era debido a factores de desviación y a los diferentes segmentos de actividades que se estaban examinando (Teicholz, Goodrum et al. 2001). Por otra parte, los deflactores y los tipos de cambio contribuyeron aún más a estos resultados poco fiables.

Esta situación hizo necesario determinar diversas variables para que la productividad del sector de la construcción fuera comparable a la de otras ramas de la industria. Por lo tanto, para comparar las condiciones del sector de la construcción con las de otras ramas de la industria, había que evaluar y comparar de forma separada segmentos individuales y valores de recurso individuales (por ejemplo, la productividad laboral anual) (Teicholz, Goodrum et al. 2001, Vogl y Abdel-Wahab 2015). Para los efectos de este análisis, se consideraron las calificaciones de la productividad laboral anual[13], ya que proporcionaban la información más fiable sobre las condiciones mundiales en ese momento. La productividad laboral anual se calcula mediante la relación entre el PIB anual y las horas de trabajo anuales agregadas (Teicholz 2001, O'Mahony y Van Ark 2003, Publicaciones-Oficina de la Unión Europea 2003).

En cuanto al crecimiento de la productividad laboral anual, en 2003 las Comunidades Europeas publicaron el crecimiento de 15 estados miembros europeos[14] (en adelante denominados UE-15) así como de los Estados Unidos (EE.UU.), reunidos entre los años 1979 y 2001 y resumidos por separado para 1979-91, 1991-95 y 1995-2001 (véase Figure 1 y Figure 2; Publicaciones-Oficina de la Unión Europea 2003).

[13] El crecimiento anual de la productividad laboral se define como el crecimiento (valor añadido) a precios constantes menos el crecimiento de las horas trabajadas. En esta sección se examina el crecimiento de la productividad laboral en contraste con la UE-15 y los Estados Unidos durante el período 1979-2001 a nivel de 56 industrias. Los cálculos básicos (valores de referencia) emplean cifras de PIB, deflactadas por los índices de precios de los Estados Unidos para las industrias de las TIC (NACE 30-33).

[14] Lista de países en la base de datos: Bélgica, Luxemburgo, Dinamarca, Alemania (Alemania Occidental - 1979-91; Alemania Unida - 1991-2001), Grecia, España, Francia, Irlanda, Italia, Países Bajos, Austria, Portugal, Finlandia, Suecia y Reino Unido.

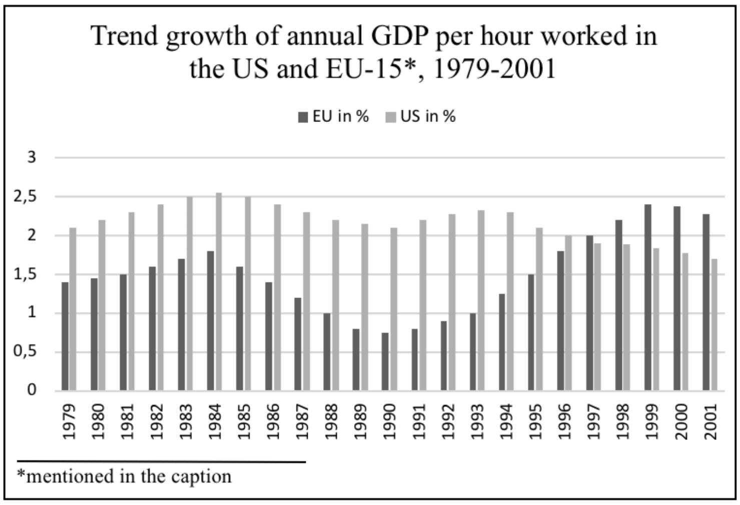


Figura 7: Tendencia del crecimiento del producto interno bruto (PIB) anual por hora trabajada - Comparación entre los mercados de la UE-15[14] y de los Estados Unidos durante los años 1979-2001; basado en (Publicaciones-Oficina de la Unión Europea 2003)

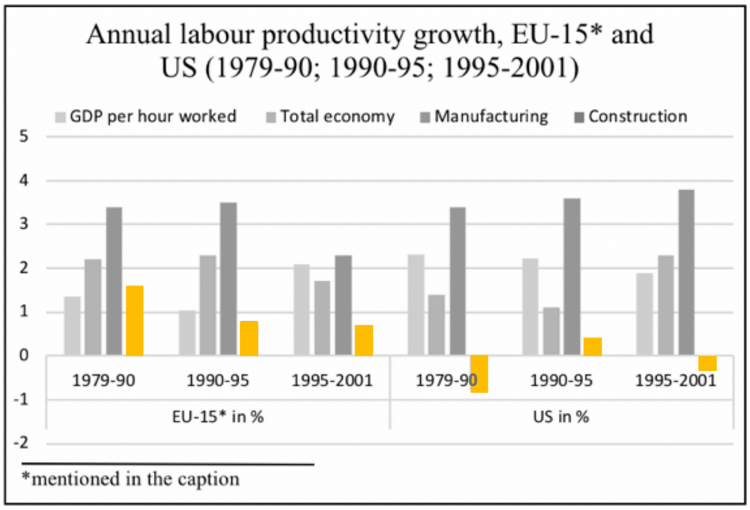


Figura 8: Crecimiento anual de la productividad laboral[13] de la economía total, la industria manufacturera y el sector de la construcción - Comparación entre los mercados de la UE-15[14] y de los mercados de Estados Unidos durante los años 1979-90, 1990-95 y 1995-2001; basada en (Publicaciones-Oficina de la Unión Europea 2003)

La Figure 1 muestra la trayectoria del PIB por hora trabajada en la UE-15[14] y en los EE.UU. entre los años 1979 y 2001. Esto ilustra que los valores de la UE fueron consistentemente mucho más bajos que los de los EE.UU. Esto continuó hasta aproximadamente 1997, después de lo cual la curva de los EE.UU. se aplana hasta cierto grado mientras que los valores de la UE aumentan considerablemente. La Figure 2 demuestra que el valor medio acumulado de la productividad laboral anual europea de todos los sectores económicos (presentado como Economía total) ha disminuido lentamente del 2,2% al 1,7%, mientras que el valor de los EE.UU. ha crecido -después de un descenso inicial- del 1,4% al 2,3% entre 1979 y 2001. En cuanto al desarrollo de la industria de la construcción, el gráfico ilustra una ligera disminución de los valores europeos del 1,6% al

0,7%, mientras que el rumbo de los Estados Unidos comenzó en el -0,8%, se recuperó hasta el 0,4% y volvió a bajar hasta el -0,3% (Teicholz, Goodrum et al. 2001, Publicaciones-Oficina de la Unión Europea 2003, Hanna y Iskandar 2017).

Estos resultados por sí solos no indicarían un progreso excepcional. Es de particular importancia la desviación considerable entre los valores de la industria de la construcción y la industria manufacturera. En la UE, la trayectoria de la industria manufacturera comenzó en el 3,4% y cayó al 2,3%, mientras que el valor de los EE.UU. aumentó del 3,4% al 3,8% en este período. Así, la desviación media de la productividad laboral anual entre las industrias manufacturera y de la construcción alcanzó aproximadamente el 2,0% en Europa y el 3,8% en los EE.UU. (Teicholz, Goodrum y otros 2001, Hanna e Iskandar 2017).

Los gráficos presentados anteriormente ofrecen una explicación general de la situación a la que se enfrentan la industria de la construcción en la UE-15 y en los Estados Unidos a lo largo de la última fase del siglo XX, que señala las debilidades fundamentales de la industria de la construcción en comparación con la industria de la producción. Si ahora se supone, como se ha descrito anteriormente, que la productividad laboral anual se calcula mediante la relación entre el PIB anual y las horas de trabajo anuales agregadas, esto indica unas prácticas laborales extremadamente ineficientes en la industria de la construcción. Las razones de ello son, por consiguiente, el resultado de la forma general en que la industria de la construcción ha atendido los requerimientos cada vez más complejos y los nuevos desafíos en las áreas de la planificación de la construcción, gestión de proyectos y ejecución de obras. Estas conclusiones también tienen un significado especial para comprender las causas fundamentales específicas que han prevalecido en la industria de la construcción hasta hoy.

2.2. Estancamiento del crecimiento a pesar de nuevas innovaciones

No obstante, también se aplicaron importantes innovaciones tecnológicas y estratégicas en la industria de la construcción hacia la segunda mitad del siglo anterior y luego se han buscado cada vez más en las dos primeras décadas del siglo actual, impulsadas por las tendencias de innovación habituales durante este período. Los métodos tradicionales de planificación de proyectos y las antiguas operaciones de gestión ejecutadas manualmente han sido transferidas a aplicaciones digitalizadas de planificación (diseño) y gestión de costos y tiempos basadas en la tecnología de la información. Como resultado, el diseño bidimensional (2D) asistido por computadora (CAD) se ha convertido en una norma generalizada para las tareas de diseño de proyectos y ha permanecido hasta hoy.

Para captar la trayectoria temporal de un proyecto, se han establecido ciertos instrumentos de programación de obras, transmitidos en gran medida por otras ramas de la industria, para simplificar las actividades de gestión de proyectos (Waly y Thabet 2003, Tomek y Kalinichuk 2015). Esta transición fue acompañada simultáneamente por el desarrollo inicial de iniciativas de mejora de la productividad y de gestión de la calidad (por ejemplo, la gestión "lean" y la gestión de la calidad total [GCT]), que fueron adoptadas de la industria automotriz y se han aplicado en el sector de la construcción desde la década de los 80's (Ballard 2000, Sacks, Eastman et al. 2004, Tanyer y Aouad 2005, Sacks, Radosavljevic et al. 2010). La utilización de los principios *lean* ha dado lugar a estructuras de proceso orientadas al flujo de trabajo que se establecieron en los proyectos de construcción y debieron contribuir a racionalizar las actividades de planificación, ejecución y gestión (Sacks, Koskela et al. 2010).

El método de planificación habitual y hasta ahora sólo posible basado en planos en papel, como los dibujos físicos en 2D y los documentos escritos a mano, se ha cambiado en su mayor parte hacia el CAD 2D (Goedert y Meadati 2008). Hoy en día, la planificación CAD se ha convertido en un aspecto obligatorio y en un factor importante para la calidad y el éxito en el sector de la construcción en general. Como resultado, se implementaron nuevas aplicaciones informáticas para beneficiarse de esta prometedora evolución (Meeran y Pratt 1993). Además, se descubrió que se podían implementar aplicaciones digitales de software y hardware para las tareas de gestión de costos y tiempo de los proyectos (Waly y Thabet 2003). El avance tecnológico y estratégico en el sector de la construcción produjo nuevos avances en el ámbito de las aplicaciones basadas en las tecnologías de la información y las metodologías de gestión y así, el desarrollo ulterior permitió poner en marcha la planificación CAD 3D (Goedert y Meadati 2008).

Desarrollado en base a la técnica CAD 2D, la planificación CAD 3D implica la generación de un modelo de proyecto tridimensional como un compuesto de objetos del modelo individual. Más allá del diseño geométrico, el modelo también contiene información numérica relativa a las dimensiones específicas del objeto (por ejemplo, longitud, anchura, altura, área, volumen, etc.). La modelación por computadora de proyectos de construcción, desarrollada por sistemas CAD 3D paramétricos, ha proporcionado rápidamente numerosos beneficios para aumentar la productividad de la construcción como, por ejemplo, la rápida creación de diferentes variaciones de diseño y alternativas de proyecto, que se han vuelto más fáciles de conseguir. Además, se pudieron obtener resultados de planificación previos, lo que ofrecía la ventaja de que los dibujos y planos no tenían que volver a dibujarse desde cero, sino que podían desarrollarse más con una escala menor del nivel de detalle (LoD) y un nivel de información aún más profundo (LoI). También se identificó una ventaja considerable en la corrección simplificada de errores, ya que los dibujos o modelos podían corregirse sin los requisitos comunes de tratamiento físico (borrando del papel), y por lo tanto no era necesario volver a dibujarlos. Además, una ilustración apenas realista del futuro edificio fue posible gracias a las características de representación proporcionadas, lo que se ha convertido hoy en día en una práctica común (Waly y Thabet 2003, Sacks, Eastman et al. 2004).

El desarrollo de la tecnología CAD 3D ha proporcionado posteriormente la base para la innovación del BIM, desarrollada desde el último tercio del siglo XX. La siguiente figura representa una herramienta de software común, que podría utilizarse para configurar un diseño arquitectónico basado en el BIM.

Se han considerado las siguientes características básicas para los modelos de la información de la construcción:

- El BIM presenta información geométrica, numérica y alfanumérica.
- El BIM está compuesto por los objetos del modelo individuales.
- La información característica de cada objeto del modelo está contenida en los atributos correspondientes del modelo.

- Tanto la información geométrica como la alfanumérica pueden ser obtenidas del modelo.
- La información del modelo puede almacenarse en bases de datos e intercambiarse entre los distintos participantes del proyecto, lo que permite realizar actividades de cooperación y sentar las bases de una fuente única de verdad (SSOT, por sus siglas en inglés).

El Ministerio Federal Alemán de Transporte e Infraestructura Digital (Bundesministerium für Verkehr und Digitale Infrastruktur, en alemán) describe al BIM de la siguiente manera: "El Modelo de la Información de la Construcción (BIM) se refiere a una metodología de trabajo cooperativo, basada en modelos digitales de estructura de una construcción, para registrar y gestionar sistemáticamente información/datos pertinentes al ciclo de vida para la comunicación e intercambio transparentes entre los interesados del proyecto o para pasarlos a un proceso posterior" (BMVI 2015). Una explicación similar fue proporcionada por la Norma del Modelo Nacional de Información sobre Construcciones de los Estados Unidos (NBIMS, por sus siglas en inglés), en la que el BIM se describía como "una representación digital de las características físicas y funcionales de una instalación, y sirve como recurso de conocimiento compartido para la información sobre una instalación, formando una base fiable para las decisiones durante su ciclo de vida desde su inicio en adelante" (Campbell 2007).

Más allá de los parámetros geométricos, el BIM también contiene atributos cruciales acerca de los objetos BIM en 3D relacionados con el proyecto, que pueden ser cambiados, modificados y actualizados por los miembros autorizados del proyecto (Goedert y Meadati 2008). La información capturada también puede ser almacenada y administrada a través de bases de datos, manteniendo los datos disponibles y manejables para su intercambio o reutilización. El modelo BIM 3D representa además el proyecto de construcción como ilustración del contenido de la base de datos (Autodesk 2002). Como tal, las aplicaciones BIM deberían aumentar la calidad del trabajo, acelerar la productividad y mejorar los resultados del proyecto a largo plazo, mientras que los costos para los implicados en el proyecto deberían reducirse y la duración del proyecto debería acortarse. Además, el BIM podría utilizarse para la gestión de proyectos, datos e información según las necesidades del cliente. Los usuarios también se benefician de las características del sistema, que ayudan a organizar los datos específicos de los proyectos según las secciones, las salas o incluso los componentes individuales y a crear una disponibilidad eficiente de datos a largo plazo (Autodesk 2002, King 2017).

Desde el desarrollo y la aplicación del BIM en el sector de la construcción, esta industria ha estado cada vez más definida por una revolución digital y del BIM. Revisando la tendencia internacional en relación con las aplicaciones BIM, se revelan importantes incentivos para la aplicación, especialmente en los Estados Unidos, Gran Bretaña, Asia oriental, la región escandinava, Alemania y varios otros países. Para establecer gradualmente el BIM en Alemania, en 2015 el BMVI introdujo un plan escalonado llamado "diseño y construcción digital"[15] (Koo y Fischer 2000, BMVI 2015). Su principal objetivo es ir transformando los actuales métodos de diseño y construcción hacia la digitalización y establecer el BIM como la nueva norma para los proyectos de infraestructura pública. Además, los métodos de planificación y construcción digitales deberían establecerse como norma nacional para los proyectos de construcción pública hasta el 2020. La institución alemana "planen-bauen 4.0" facilita el principio central, por lo que la "ejecución práctica de la construcción" sólo puede comenzar cuando se haya completado el "proceso de construcción digital". Esta declaración aclara los requisitos futuros del sector de la construcción y define los desafíos a los que los actores de la cadena de valor de la construcción deben ajustarse en el futuro (Koo y Fischer 2000, Autodesk 2002, BMVI 2015).

Para lograr una solución sofisticada y probada referente a la planificación y gestión de proyectos, la sinergia de los métodos anteriores representa una opción obvia. Por lo tanto, más allá del modelo BIM 3D se debe considerar todo el ciclo de vida del proyecto, incluyendo el tiempo (4D) y los costos (5D). Esta innovación evolucionó en el desarrollo del concepto de 4D y 5D, con lo que el diseño del proyecto está estrechamente relacionado con los costos del proyecto y los plazos de ejecución (Fan et al. 2015; Sánchez-Rivera et al. 2017; Fischer y Aalami 1996). La sinergia entre los enfoques de BIM y 5D dio como resultado la metodología BIM 5D, que además ofrece la posibilidad de simulación de secuencias de construcción virtuales basadas en el modelo BIM 3D y la correspondiente información de costos y plazos del proyecto (Fischer et al. 1996; Koo et al. 2000; VDI, 2018).

[15] El plan de pasos ha sido desarrollado por el "planen-bauen 4.0 - Gesellschaft zur Digitalisierung des Planen, Bauens und Betreibens mbH" bajo la autoridad del BMVI.

En 1996, Fischer et al. investigaron y describieron la mejora del diseño y la gestión de la construcción del 4D (Fischer et al. 1996; Koo et al. 2000). El método de planificación 4D consiste en el diseño de un modelo CAD 3D combinado con aspectos de tiempo y programación de obra. La idea básica es vincular estrechamente el progreso del cronograma o incluso fechas individuales (por ejemplo, la fecha de inicio/fin del proyecto; hitos y plazos; etc.), con los correspondientes objetos del modelo de proyecto en 3D para lograr un escenario de desarrollo y ejecución del trabajo del proyecto transparente y manejable (Fischer et al. 1996; Koo et al. 2000). En lo que respecta a la identificación de los choques del cronograma y el análisis de las interferencias, el enfoque del modelo 4D resultó ser óptimamente aplicable, como demostraron Koo et al. en su investigación publicada en 2000 (Koo y Fischer 2000).

Además, la gestión de los sitios de construcción ha mejorado considerablemente gracias a la aplicación del método 4D, como sostuvieron Chau et al. en 2004 (Koo y Fischer 2000, Chau, Anson et al., 2004). Estas actuaciones y mejoras verificables han contribuido también a beneficiar a una nueva dimensión, que en consecuencia ha dado lugar al ya mencionado enfoque de planificación 5D[16]. Este método se caracteriza por un modelo 3D BIM o CAD del proyecto en cuestión (3D); el aspecto temporal para una planificación virtual y realista del cronograma del proyecto (4D); y los factores correspondientes de coste para presentar el desarrollo del coste del proyecto en relación con las actividades de ejecución asignadas (5D). De acuerdo con el procedimiento del proyecto, de conformidad con los requisitos del modelo 3D y el calendario previsto del proyecto, el gráfico de costos o del cronograma podría mostrar los valores actuales de los costos provisionales del proyecto en cada punto en el tiempo a lo largo de la planificación virtual del proyecto. A partir de ello, se ha podido obtener una visión general del estado del proyecto clara y comprensible en gran medida (Tanyer y Aouad 2005, Kuenzel, Teizer et al. 2016, Comisión Europea 2017). La demanda de una correlación entre los asuntos de

[16] Recientemente se han desarrollado otros enfoques, como los de sostenibilidad (6D) y gestión de instalaciones (7D), pero no deben tenerse más en cuenta para mantener el alcance de la presente tesis dentro de los límites razonables (Redmond, A., Hore, A., Alshawi, M., and West, R., (2012) "Exploring how information exchanges can be enhanced through Cloud BIM." Automation in Construction 24: 175-183; Fan, S. L., Wu, C. H., and Hun, C. C., (2015) "Integration of cost and schedule using BIM." Journal of Applied Science and Engineering 18(3): 223-232; Sánchez-Rivera, O. G., Galvis-Guerra, J.A., Porras-Díaz, H., Ardila-Chacón, Y.D., Martínez-Martínez, C.A. (2017) "BrIM 5D models and Lean Construction for planning work activities in reinforced concrete bridges" Tunja-Boyacá, Colombia, Revista Facultad de Ingeniería. 26: 39-50.).

planificación, costes y programación de obra se ha convertido así en un requisito importante para evitar que el diseño del proyecto, así como los costos correspondientes y las actividades de programación se desvíen.

En el pasado se han desarrollado e implementado numerosas y diferentes soluciones de programación basadas en la tecnología de la información en el sector de la construcción; aunque inicialmente no se destinaron para aplicaciones 5D, se han utilizado cada vez más con este propósito. Estas herramientas de programación se basan en gran medida en el principio de cascada (Echeverry et al. 1991; Tory et al. 2013). Este principio sigue una estructura estrictamente jerárquica basada, en general, en la relación entre tareas cronológicas y las fechas de ejecución o duración. Su mayor ventaja radica en su alta fiabilidad de planificación, que es obligatoria para la gestión de proyectos a gran escala (Tomek et al. 2015). Debido a la organización habitual, este método es ideal para proyectos con requisitos de procedimiento consistentes y mejoras reconocibles a largo plazo (Echeverry et al. 1991). Los procedimientos rápidos de cambio y las operaciones ad hoc obstruyen este progreso. Los ejemplos más comunes de aplicaciones basadas en cascadas incluyen el diagrama de Gantt, la línea de equilibrio o el método de la ruta crítica (Tory et al. 2013).

Otro logro revolucionario fue alcanzado gracias a la transformación e implementación del enfoque *lean* en el sector de la construcción. Inventado originalmente por Taiichi Ohno, ingeniero de producción de la Toyota Motor Company, los principios generales del enfoque "lean" se clasifican en cinco puntos principales: los principios "lean" de James P. Womack, Daniel T. Jones y Daniel Roos (Womack 1990, Womack y Jones 2003). El siguiente gráfico ofrece una visión general de los cinco principios básicos del enfoque *lean* y, además, proporciona ejemplos individuales de implementación (Figure 3):

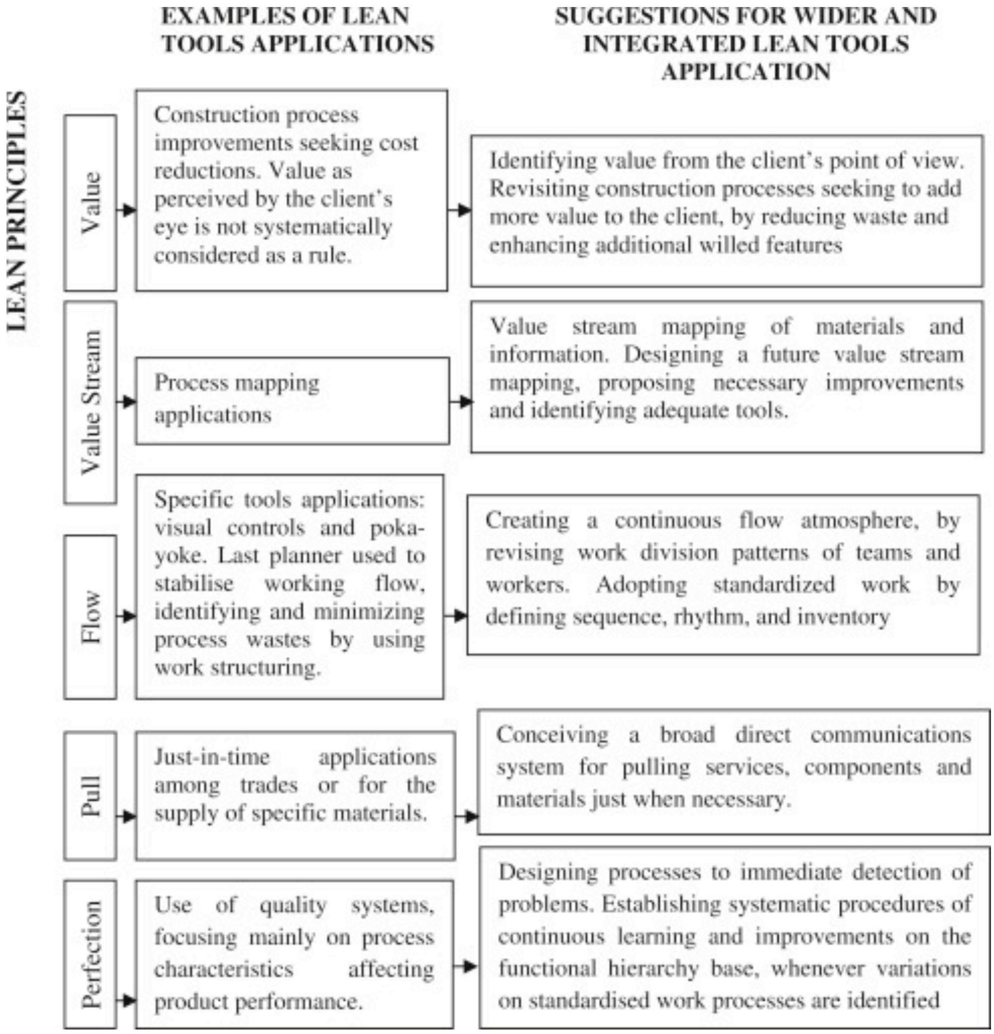


Figura 9[17]: Los cinco principios lean (Oladapo, Oginbiri et al. 2019)

El objetivo del enfoque *lean* es aumentar el valor de los clientes a través de la eliminación total de cualquier tipo de desperdicio y optimizando la cadena de valor general, incluyendo todos los factores correspondientes o influyentes (Womack 1990, Womack y Jones 2003). Debido a su éxito considerable, los principios *lean* fueron transferidos e implementados a la industria de la construcción a lo largo de las dos últimas décadas. Según las normas de la Asociación de Ingenieros Alemanes (VDI) (VDI 2553 - versión en borrador), la construcción *lean* describe la transformación del enfoque de gestión "lean" como un sistema de producción integral para su uso en las tareas de planificación y ejecución de la construcción, incluyendo todos los procesos

[17] Esta cifra fue proporcionada por el artículo "Oladapo, A. A., Oginbiri, O. y Goulding, J.S. (2019). Principios *lean* en la construcción (Capítulo 12), Elsevier". - con el permiso amistoso de Elsevier.

participantes, así como la cooperación con cada una de las partes interesadas involucradas. La puntualidad, el cumplimiento de los costes, la transparencia, la calidad del proceso y de la ejecución del trabajo, y los valores de rendimiento representan los factores clave para lograr el éxito de los proyectos entre empresas. Además, el objetivo de la construcción *lean* se centra en la estabilización, optimización y aceleración de los flujos de trabajo del proceso de construcción, así como en la logística de materiales e información (VDI 2017).

Un resultado significativo de la filosofía *lean* fue el desarrollo del Last Planner System (LPS) alrededor del cambio de milenio. El LPS busca una mejora significativa de la ejecución del proyecto, la gestión del sitio de construcción y la fiabilidad del programa de ejecución. El concepto central consiste en una organización de tareas de proyectos en equipo que incorpora la experiencia práctica de los capataces y los directores de obra y utiliza una estrategia estructurada flexible para la orden de ejecución de los oficios de la construcción (Ballard 2000, Howell, Ballard et al. 2004). Avanzando hacia este objetivo, Ballard introdujo el enfoque inicial de "Last Planner" (Último Planificador) en 1993, que se vio sustancialmente influido por el Sistema de Producción de Toyota y la teoría de producción de Lauri Koskela (Ballard 1993, Ćwik and Rosłon 2017). Este enfoque se continuó desarrollando y finalmente fue presentado por Ballard en el 2000 como el LPS para su uso en la gestión de las actividades de ejecución de la construcción (Ballard 2000, Hamzeh, Saab et al. 2015) - véase la Figure 4:

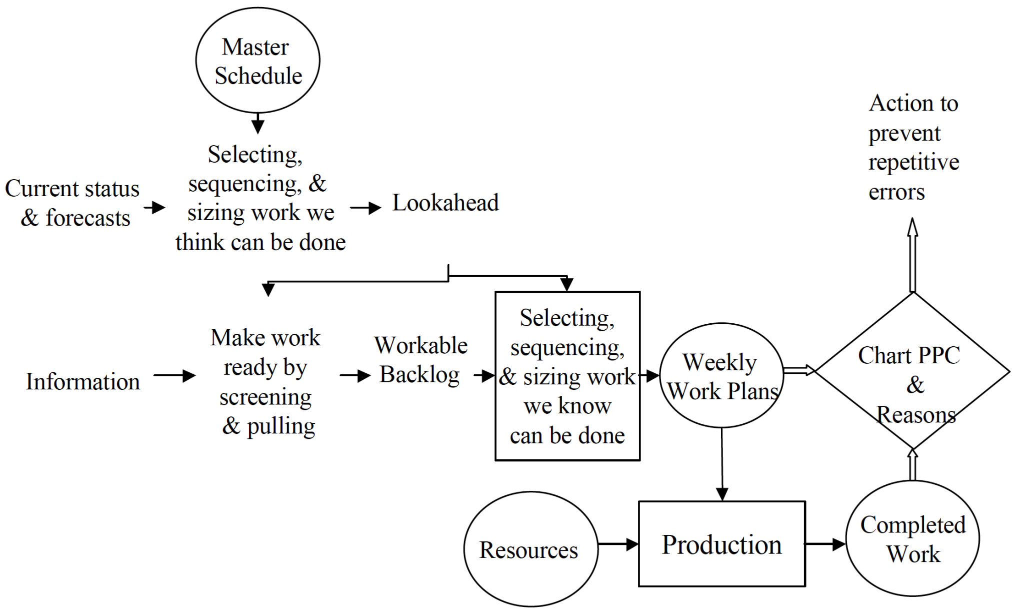


Figura 10: Last Planner System (LPS) con el proceso de previsión resaltado (Ballard 2000)

El LPS se basa generalmente en los principios cruciales *lean* de reducción de desperdicios, pull-planning (planificación de tiro), mapeo de la corriente de valor (VSM, por sus siglas en inglés) y entrega justo a tiempo (JIT, por sus siglas en inglés). Además, el LPS se utiliza para planificar, supervisar y controlar los procesos de ejecución de la construcción. En las primeras etapas, se presta especial atención a la elaboración y utilización de planes de trabajo semanales, elaborados por los directores y capataces del proyecto en el papel clave del último planificador. A continuación, se establecen planes de previsión para controlar y mantener los flujos de trabajo. De este modo, se pasa de la mejora de la productividad a la mejora de la fiabilidad de los flujos de trabajo (Ballard 2000, Ballard y Howell 2003, Shang y Pheng 2014).

El LPS se basa también en la metodología ágil, que sigue un modo de acción de máxima flexibilidad. Su característica básica es que los proyectos se desarrollan paso a paso por equipos interdisciplinarios y organizados de forma descentralizada de acuerdo con "sprints" consecutivos (Owen et al. 2006). El propósito es racionalizar los esfuerzos de la gestión de proyectos y mantener una gran flexibilidad incluso para los cambios en las últimas etapas de los proyectos, a fin de satisfacer rápidamente las necesidades de los clientes o ejecutar actividades ad hoc. Las deficiencias de los métodos ágiles pueden encontrarse en la falta de transparencia de los valores de las tareas abiertas. Además, los métodos ágiles actuales todavía no se han adaptado y transformado en aplicaciones razonables basadas en la tecnología de la información para su utilización en el sector de la construcción (Ballard, 2000; Ballard et al., 2003).

El objetivo principal del LPS es respaldar la comunicación y la colaboración entre los capataces y los directores de obras y mejorar las relaciones de confianza dentro de los entornos de los equipos de obra en los diferentes niveles de los proyectos, haciendo visibles los próximos temas para su aclaración antes de que se vuelvan problemáticos o intensifiquen. La aplicación del LPS contribuye a aumentar la posibilidad de contar con procedimientos de planificación y flujos de trabajo de proceso fiables además de demostrar que las relaciones personales y la presión de los compañeros de trabajo pueden influir en este proceso (Hamzeh, Saab y otros 2015, LCI 2015). En 2015, Mossman resumió ocho razones ejemplares por las que el LPS es valioso para su aplicación en proyectos de construcción (Mossman 2015):

- La duración del proyecto se reducirá.
- Los costos deben ser manejados mejor.
- La entrega de los proyectos será más segura.

- Se reducirá el estrés de los directores de proyectos.
- Los programas de producción se volverán más predecibles.
- Se mejorarán los procesos de producción en general.
- Los cronogramas de los proyectos se vuelven fiables para permitir la entrega justo a tiempo.
- El enfoque de la ruta crítica se vuelve redundante.

El LPS se centra en los procesos de ejecución de obras sin perturbaciones, en los que se anima a los capataces y, en algunos casos, a los obreros a que elaboren planes detallados para las próximas tareas en la obra. Estos planes se revisan antes de que se ejecute el trabajo en la obra. Además, los problemas y limitaciones esperados o inminentes se eliminan en sesiones de trabajo en equipo. Los compromisos que se adquieren entre sí en las reuniones del equipo se verifican en cuanto a los aspectos de tiempo y, además, se contrastan para evitar ambigüedades. Si el equipo lo permite, esos compromisos se transfieren a hitos y se añaden al calendario de ejecución del trabajo y, a partir de entonces, es absolutamente obligatorio que la persona o el equipo responsable ejecute las tareas correctamente y a tiempo (LCI 2015, Russell, Liu y otros, 2015). Teniendo en cuenta estos logros, podría, razonablemente, esperarse un fuerte aumento de los valores de productividad en las dos primeras décadas del siglo actual. Sin embargo, el progreso del gráfico de productividad tomó un rumbo bastante diferente, como se ilustra en la Figure 5 y la Figure 6:

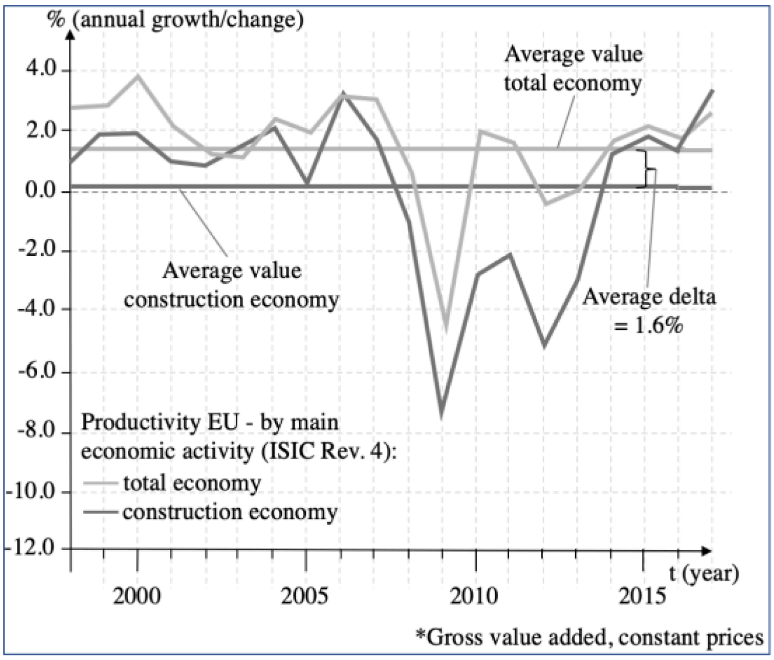


Figura 11: La productividad anual de la UE; economía total frente a economía de la construcción; Figura basada en (OCDE 2020)

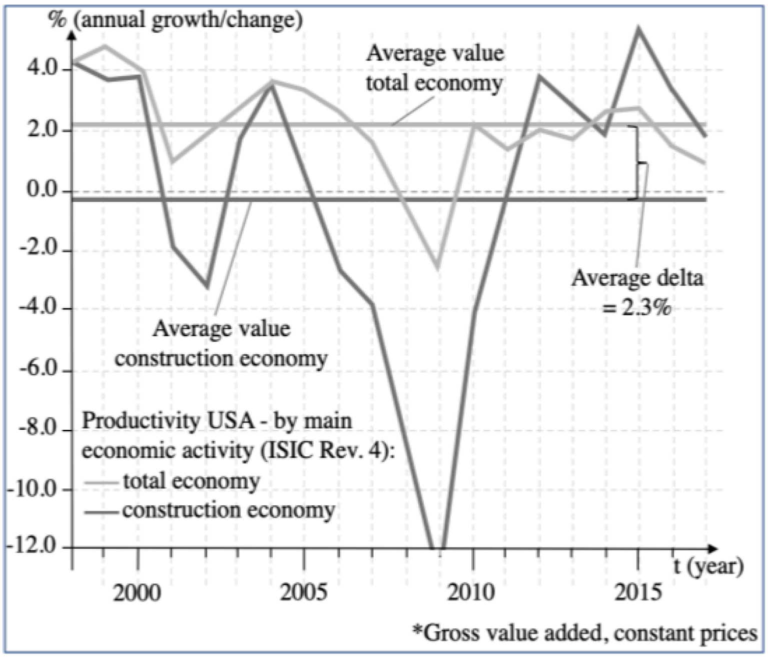


Figura 12: Clasificación de la productividad anual de los EE.UU.; economía total vs. economía de la construcción; Figura basada en (OCDE 2020)

A fin de demostrar el progreso continuo de las mejoras que van aumentando lentamente y que todavía predominan en el sector de la construcción, se representan más arriba los índices de productividad (valor añadido bruto a precios constantes) de 1995 a 2017. Estos valores fueron registrados continuamente dentro de este período por el Departamento de Estadística de la Organización de Cooperación y Desarrollo Económicos (OCDE; la OCDE proporciona datos comparables de la UE y los Estados Unidos sólo entre 1995 y 2017; OCDE 2020). Durante este tiempo, el crecimiento promedio anual de la productividad del sector de la construcción en Europa fue del 0,1%, mientras que el valor promedio de los Estados Unidos fue del -0,2%. En comparación con la economía total, estos valores indican una desviación media del 1,6% en la UE y del 2,3% en los Estados Unidos. Además, los valores de productividad anual del sector de la construcción de los Estados Unidos aumentaron entre 2012 y 2019, lo que resalta los factores responsables de los pasivos desencadenantes de errores en la industria de la construcción (OCDE 2020).

A pesar de este gran número de innovaciones y mejoras estratégicas significativas aplicadas en la industria de la construcción en los últimos años, como indican los gráficos presentados, no se ha logrado todavía ningún cambio considerable en el aumento de la productividad en este sector de la construcctión. Dado que este resultado es difícil de comprender, es necesario realizar una investigación intensiva de las posibles causas. Con ese fin, se deben revisar las investigaciones realizadas anteriormente y la bibliografía proporcionada para determinar las causas fundamentales de este desarrollo. Además, los enfoques de planificación, gestión y ejecución de proyectos aplicados actualmente deben analizarse en ese mismo contexto.

3. State of the Art

3.1. Literature Investigation

The previous section provided reliable justification about persistent difficulties and weaknesses in the construction industry due to various sources of errors, which disrupt construction project lifecycles and indicate a high degree of inefficient activities. In the following chapters, a general and specific investigation is conducted to uncover the weaknesses and sources of error in the construction industry regarding problematic working methods. In particular, the reasons for the high degree of missed deadlines and inaccurate project management are examined. Before the currently known and applied project planning and management methods are evaluated in detail, however, a deep literature study is provided to outline the present state of research and development.

Subsequently, a detailed process analysis is performed based on an exemplary project scenario, which represents the course of a construction project in common use today. Weak points and missing interconnections in the overall process are thus identified. Subsequently, a further process chart is presented to demonstrate critical possibilities for improving schedule reliability. Moreover, previously unused optimization potential for enhanced project management is described.

Increasing complexity of process workflows, a high number of participant stakeholders, continuously changing planning requests, and rising technical requirements result in increasingly intricate project conditions and growing temporal issues (Oesterreich et al. 2016). Flow in progression is thus interrupted, assembly times are exceeded, and costs run out of control. According to Oesterreich et al. (2016), structural issues within the building sector represent a root cause preventing sustainable project success. These can be allocated to the following six subgroups (Oesterreich and Teuteberg 2016):

- Complexity
- Uncertainty
- Short-term thinking
- Insufficient commitment
- Fragmented supply chain
- Cost and time exceeding

Arayici stated in 2012 that the construction sector has rarely managed to develop and implement future-oriented innovative technologies or strategies in order to deal with the challenges of uncertainty and to be in line with common standard implementations. Due to conservative and cumbersome culture and strong resistance, when it comes to advancements, changes remain difficult to be implemented (Arayici and Coates 2012).

Kraatz et al. stated in 2014 that short-term thinking has prevailed, as individual projects generally consist of loosely coupled project team settings, which work closely together for the period of a particular project, but are not long-term focused in cross-company or project cooperation (Kraatz, Hampson et al. 2014, Oesterreich and Teuteberg 2016). Project-concerned contractors are selected by procurement procedures based on competition acts, whereby the composition of project stakeholders is always new and alwasys different. The same conditions prevail for subcontractors and product suppliers.

For many project participants, these circumstances are additionally affected by short-term commitment to the tasks at hand caused by various and often not self-inflicted reasons. Oppong et al. stated in 2017 that, since project commitment has not been focused on broadly in the building sector in recent decades, there is a deficiency of elaborative tools to improve project performance (Dubois and Gadde 2001, Oesterreich and Teuteberg 2016, Oppong, Chan et al. 2017).

Buvik et al. determined in 2017 that successful project outcomes are directly dependent on both team and project commitment, where team commitment is subjected to a social framework and project commitment pertains to the work itself (Buvik and Tvedt 2017). Project stakeholders face comparable challenges of complicated collaborations along a project lifecycle. Project teams are typically cross-functional and composed of various specialized team-member constellations relevant to the project's completion. Generally, they work together for the very first time and usually just for a limited period of time on a project. As such, projects suffer from coordination problems, unsuccessful project management activities, exceeded deadlines, and poor project outcomes (Buvik and Tvedt 2017).

In 2013, an investigation by Ehrhardt et al. revealed that project commitment significantly consolidates team performance in cross-functional projects (Ehrhardt, Miller et al. 2014, Buvik and Tvedt 2017). This finding has been applied in recently developed management methods (LPS as well as KanBIM), with a special focus placed on execution project members in order to implement a reliable project workflow. Both, project and team commitment could be achieved by encouraging the leading team members on site to develop a sense of ownership over the tasks they perform. In effect, this means that the worker assumes decision-making responsibility to add or elaborate tasks in detail and to commit to what could be accomplished within a specified timeframe (Ballard 2000, Shang and Pheng 2014).

This reveals commitment to be a significant variable that contributes to improving project results and considerably enhancing quality along with cost and time savings (Leung, Chen et al. 2008, Kim and Nguyen 2018). If this innovation is taken seriously, companies could improve their productivity and streamline project performance to significantly improve project outcomes. In order to benefit from this potential option, however, team members should encourage this commitment of their project team leaders, site managers, and foremen (Ballard and Howell 2003, Mossman 2015).

A further important construction-specific issue concerns the unreliability of the supply chain connection to the project workflow (of particular importance besides material delivery is the timely provision of information or data, such as timely delivery of construction execution plans). Planning teams deal with information gaps that hamper the delivery of mature, practicable, and appropriate planning information; as such, exceeding deadlines become inevitable from the outset. Moreover, postponements of planning delivery dates may create a starting point for a sequence of further errors (Arayici and Coates 2012, Oesterreich and Teuteberg 2016). Numerous factors, such as urbanistic approvals or the issuance of building permissions, are also partially unpredictable and could trigger time delays for project kick-offs or process-workflow interruptions. The majority of contractors and small or medium-sized companies sourcing their goods and services via highly fragmented and unstructured supply chains rarely collaborate with the project management team. Undermining or dissolutions of work execution schedules, deadline overruns, and additional project costs are thus difficult to prevent in the current method (Oesterreich and Teuteberg 2016, Buvik and Tvedt 2017, Kim and Nguyen 2018).

Furthermore, insufficient limitations for customer requests in late project execution stages disturb or, in the worst case, corrupt proper supply chain workflows. Therefore, unaccomplished obligations and increasing risks of failing project success, as well as persistent mismanagement, becomes unavoidable. In 2018, Kim et al. investigated how proper supply chain management influences the performance of construction projects, finding that “the supply chain relationship traits have a significant positive impact on project performance” (Kim and Nguyen 2018). This finding may support project teams in identifying and eliminating the core attributed issues, which will subsequently help increase supply chain and project performance dependencies in order to gain proper and undisturbed project workflows (Leung, Chen et al. 2008, Kim and Nguyen 2018).

Moreover, the Voice of the Customer is entitled to set changes until the very end of a project, resulting in re-planning, demolition operations, unpredictable extra expenses, and schedule postponements (Kannengiesser and Roxin 2016). The well-known TQM 1-10-100 Rule, illustrated in Figure 13, explains how re-planning affects the cost evolution during a project’s progression:

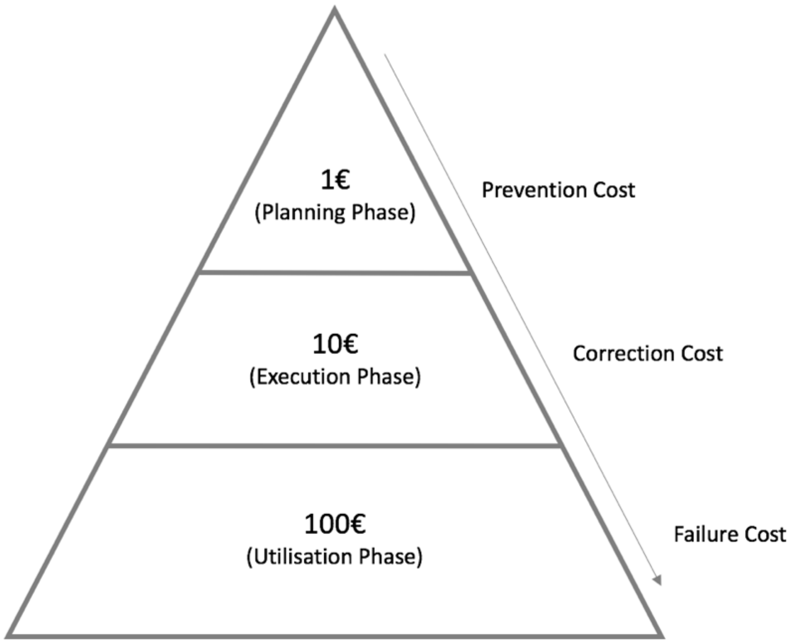


Figure 13: Cost development caused by re-planning; 1-10-100 Rule – according to (Ross, 2004)

The graph demonstrates the influence on cost development due to changes in the building targets implemented either early or late in the construction process. Related to the cost development, the extension of time can be represented equivalently, as presented in Figure 14 (Ross 2004). This offers an immediate indication of the requirement for a proper and extensive construction planning:

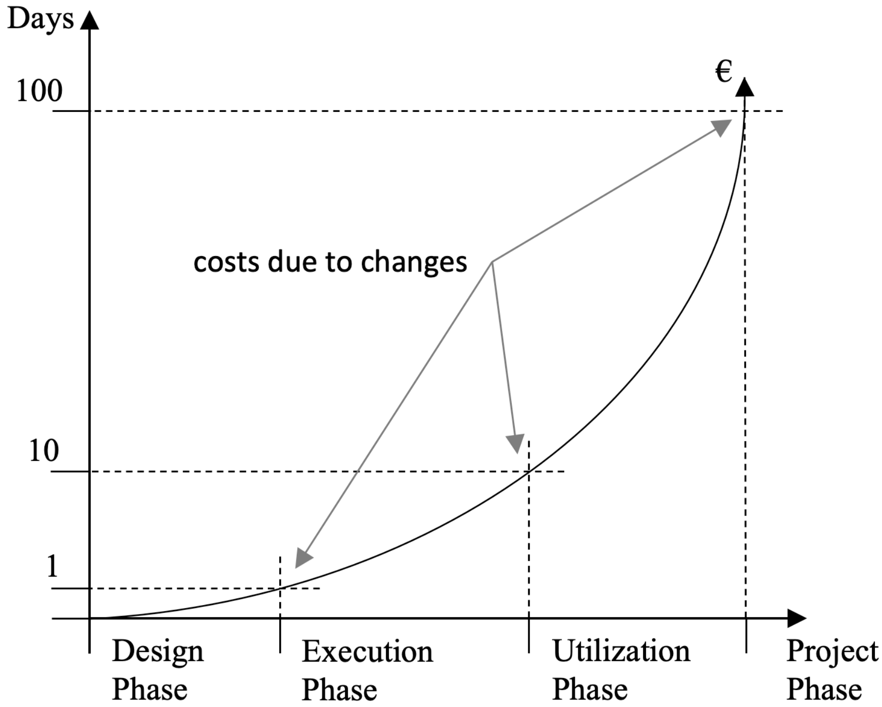


Figure 14: Extension of time caused by re-planning; 1-10-100 Rule – own illustration; 2018 – in accordance to (Ross 2004)

Mostly building projects are affected by extremely tight time and budget constraints. As such, proper and sophisticated planning is indispensable to enable flow for processing the project. Financial penalties caused by delayed or exceeded schedule deadlines could also produce a lasting effect on the project outcome and, moreover, could corrupt the project's success. An investigation regarding financial penalties of construction projects, conducted by Golob et al. in 2013, pointed out that an average value of 2–5% and a maximum value of up to 15% of the total project costs became due caused by project schedule overruns (Oesterreich and Teuteberg 2016).

An investigation by Kuenzel et al. (2016) indicated that nearly 90% of the analyzed construction projects suffered from coordination problems and unsuccessful project management and further exceeded project deadlines (Kuenzel, Teizer et al. 2016). Oppong et al. (2017), meanwhile, identified stakeholder's insufficient commitment to the project as an important reason for project failures (Oppong, Chan et al. 2017). Further investigative approaches have revealed that planning issues, complications in project organization, and stakeholder disagreements cause projects to exceed their schedules and budgets. Increasing project complexity, constantly changing customer requests, and a wide variety of regulations result in even greater planning and execution efforts (Assaf and Al-Hejji 2006, Howell, Ballard et al. 2011, Larsen, Shen et al. 2016, Kim and Nguyen

2018). Moreover, the sophisticated technical requirements and high quantity of project participants greatly affect the deployment efforts in project management and control.

Sambasivan stated in 2007 that the issue of delays and schedule overruns in construction projects can be understood as a global phenomenon, with conclusive evidence provided by numerous studies (Sambasivan and Soon 2007). A paper by Olawale and Sun (2015) evaluated several international investigations concerning exceeded costs and mismanaged schedules in construction projects; according to this paper, Hoffman et al. determined in 2007 that 72% of 332 public US facility projects were delivered late, and 47% exceeded the project timeline by more than four months (Hoffman, Thal et al. 2007, Olawale and Sun 2015). The German Federal Ministry of Construction conducted an analysis between 2000 and 2015, identifying exceeded costs and mismanaged timelines in 300 building projects (>10 m EUR). Only 65% achieved their scheduled targets (CIOB 2008). According to an investigation by Assaf and Al-Hejji (2006), 59% of 76 evaluated projects in Saudi Arabia were considered delayed (Assaf and Al-Hejji 2006).

However, the examples are not solely negative. In 2006, Salem et al. presented a construction project case study where the application of specific agile organization and lean construction approaches (applied lean construction elements like the LPS; Increased Visualization; Huddle Meetings; First Run studies; 5S; Fail-Safe for Quality) brought the project's progression up to three weeks ahead of schedule (BMUB 2016). Furthermore, Thomas et al. found as early as 2002 that significantly reduced project duration of approximately 30% is achievable through sustainable project management improvements (Salem, Solomon et al. 2006).

Hanna et al. (2010) and Hwang et al. (2011) identified advantages in thorough pre-planning, which led to improved work execution quality, increased productivity values, and reduced project duration (Hanna and Skiffington 2010, Hwang and Ho 2011). Nevertheless, the main causes for project delays remain under investigation. Doloi (2012), Braimah (2014), and Larsen (2016), in addition to many others, investigated the significant impediments that directly influence a project's schedule (Doloi, Sawhney et al. 2012, Braimah 2014, Larsen, Shen et al. 2016). The results of these studies indicated weak design elements; poor project planning, site management, and project control; insufficient contractor experience; contract payment problems; equipment availability; weather or environmental conditions; and material supply issues as the primary causes for project delays (Doloi, Sawhney et al. 2012, Braimah 2014, Larsen, Shen et al. 2016).

A study by Gebrehiwet et al. (2017) revealed 52 of the most likely reasons for project delays, of which ineffective project scheduling ranked number two behind deficient project planning (Gebrehiwet and Luo 2017).

This investigation represents the international situation within the construction industry and provides information regarding general and fundamental problems in construction project planning and execution (Ballard 2000). Regarding research and development within the construction industry, the European scoreboard of research and development stated in 2015 that the construction industry ranks under the lowest branches, with a (R&D)-net-sales value < 1% (Hamzeh, Saab et al. 2015, Oesterreich and Teuteberg 2016, WEF 2016, European-Commission 2017). This result is particularly important, as in most countries, the construction sector is one of the largest employers, with continuously growing influence on national and international economies. Current challenges of growing technical complexity of buildings, strict environmental requirements, and the provisions of constitutional rules and regulations create increasingly unpredictable circumstances in construction project management. From this, excessive delays and budget overruns represent the most common, but not the only, results (Ballard and Howell 1998, Ballard and Howell 2003, Oesterreich and Teuteberg 2016). Moreover, weaknesses in project design and inadequate schedule and cost management appear to be particularly noteworthy regarding the root causes of errors. The inevitable consequences of these differences between planned and actual values lead to unforeseeable and unexpected additional cost and time requirements, and thus to an increasing risk to project success. In order to further investigate and narrow down the described causes, current project management methods and the most recent solution approaches should be examined in the following.

3.2. Analysis of current Project Management and Schedule Approaches

3.2.1. Waterfall-based Methods

To manage and control construction projects, certain tools and methods—mostly IT-aided and cross-industry applicable—have been developed and implemented in the construction sector in recent decades (Sambasivan and Soon 2007). The core objective of project scheduling is to assign the start and end dates for individual or cumulative activities and to indicate when these activities must be finished to be delivered on time (Cox, Blackstone et al. 1992). To this end, the work breakdown structure method is valuable for gathering and structuring the required project execution activities. Even though this method features no specific time references, it provides a general framework for schedule development and enables project management, monitoring, and control options (Diekmann and Thrush 1986). A common and widespread scheduling tool is the bar chart or bar diagram—also known as Gantt chart or Gantt diagram—which graphically represents the connection between planned and actual work performance and whether activities are on, behind, or ahead of schedule (Cox, Blackstone et al. 1992). Further common methods include the critical path method, line of balance, linear scheduling method, or the network diagram (Herrmann 2006, Castro-Lacouture, Suer et al. 2009, Su and Lucko 2015, Tang, Sun et al. 2018).

First and foremost, these tools are based on the waterfall principle, the main characteristic of which concerns a strictly hierarchical embossed organization (priority based) according to the ratio between a chronological task order and appropriate task durations. Each task is provided by a clearly defined start and end date, after which dependencies on other tasks can be determined (Herrmann 2006). Waterfall systems operate according to the push principle, which releases tasks, materials, or information into preassigned procedures or scheduling systems (VDI 2017). This method is ideally suited for projects featuring consistent or repetitive proceedings and recognizable long-term interventions due to the regular organization (Echeverry, Ibbs et al. 1991). The basic principle of a waterfall-based structure is represented by Figure 15 below:

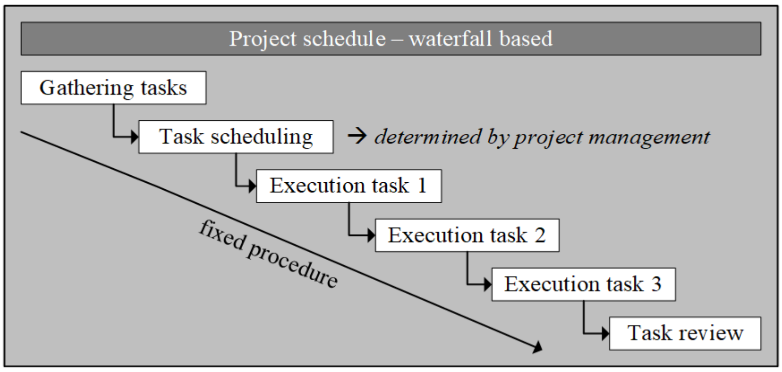


Figure 15: Waterfall-based project scheduling (according to Tory et al. 2013)

Due to the required top-down structure, subsequently added activities could rapidly cause postponements and disturb project flow. Tory et al. thus stated in 2013 that schedules should be dynamic documents that can be frequently changed and adjusted in accordance with the project's progression and its various requirements. However, this has turned out to be nearly impossible due to the static structures and the multitude of different links and dependencies characteristic of waterfall-based scheduling methods (Tory, Staub-French et al. 2013).

In 2005, McKay and Wiers (2005) indicated that the amount of dynamic and unpredictable activities and the capacity for compensation should be considered when determining a project's scheduling method (Herrmann 2006, Owen, Koskela et al. 2006). Accordingly, a significant disadvantage of the waterfall system concerns its non-dynamic ability to react quickly to rapidly changing procedures or ad-hoc operations triggered by unpredictable events during a project's lifecycle. Disregarding these disadvantages, waterfall-based scheduling methods are still widespread in the construction industry and cause many of the time-related issues because of the previously indicated reasons (Tory, Staub-French et al. 2013).

3.2.2. Agile Methodologies

The waterfall approach is contrasted by the agile methodology, which follows a maximum dynamic mode of operation. In this method, project requirements and tasks are gathered and listed in the initial phase. An iterative process—consisting of task planning, execution, and revision steps—defines the project's organizational structure, as illustrated in Figure 16:

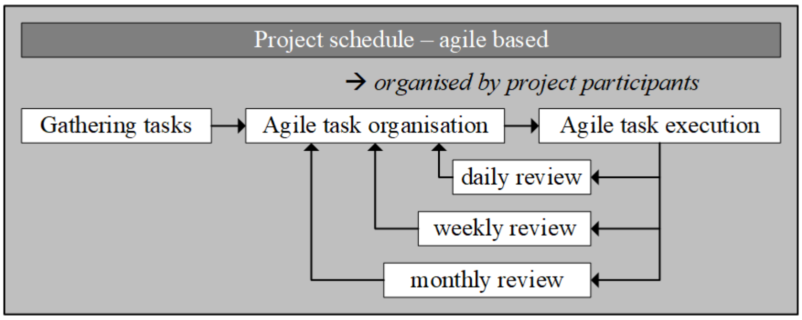


Figure 16: Agile-based project scheduling approach (according to Ballard 2000)

Intermediary assessments can also be implemented to revise short-term activities (Owen, Koskela et al. 2006). Sanchez et al. (2001) described agility as a cooperative and synergetic strategy organizing the processing and delivery of customer-specific high-quality goods and services even in dynamic or unpredictable project environments. In terms of project team's participation and composition, the multi-flexible method proves particularly advantageous, as a previously well-structured organization enables transforming constituent project participants into multi-skilled and cross-functional teams with participating members from both (internal/external) customers and suppliers (Sanchez and Nagi 2001).

In this way, the purpose of this method is to streamline project management efforts and keep flexibility high, even with changes in late project stages (VDI 2017). According to Sacks et al. (2010), the basic methodology behind multi-flexible management is the lean approach, which was implemented in and adapted to the construction sector in order to "reduce variation, improve coordination, implement flow, establish pull, and to cut down various forms of waste in construction projects" (Sacks, Radosavljevic et al. 2010). Some potential deficiencies of agile methods include difficulty predicting a project's progression and lacking the transparency of timescale objectives due to the flexible organization of task execution (Ballard 2000, Ballard and Howell 2003). With the introduction of the LPS in 1993/94; however, the first official multi-flexible method was applied to the construction industry (Ballard 2000). Implementing master and phase-schedule plans based on the general principles of the agile methodology has thus contributed to more organized project execution and connected production targets with project proper working structures. Key advantages of the LPS include significant improvements in information exchange and strengthened cooperation between project/site men, who gather in monthly and weekly meetings to solve upcoming issues before they become critical (Ballard 2000).

Due to its multi-flexible characteristics, the LPS improves schedule reliability and is ideally suited for complex, dynamic, and uncertain project conditions (Mossman 2015). However, a critical aspect of this method concerns its limited implementation potential, as the system was primarily developed for project execution duties, and is thus primarily applicable to a project's execution phases. Furthermore, insufficient establishment of the lean principle to *pursue perfection* represents a persistent issue preventing the requirement of continuous improvements and optimization of the datasets for future project planning. Weekly work plans also do not provide provisions for conducting any experimentation; thus, the LPS learns from failure rather than from success (Sacks, Radosavljevic et al. 2010).

Moreover, the knowledge gained through work execution is not stored and organized in databases and cannot be used in further projects (Echeverry, Ibbs et al. 1991, Ballard and Howell 2003, Tory, Staub-French et al. 2013). According to Sacks et al. (2010), the LPS reduces variation through the early consideration of upcoming issues, but fails to implement *pull* by disregarding important indications (signals) generated by downstream operations. Additionally, the LPS rarely provides a clear evaluation of the open tasks list, which potentially causes imprecise project status indications (Liker 2003, Sacks, Radosavljevic et al. 2010).

Moreover, when examining the LPS, it is noticeable that a certain phrase is used frequently, indicating that implementing the LPS "*has brought the project ahead of schedule*" (Mossman 2015). Consequently, it must be stated that this does not contribute to the desired goal of schedule reliability, which comprises one of the main targets of the Lars planner system. Precise planning strictly adheres to the timeline and anticipates positive or negative changes or impacts, calculates these from the outset, and keeps solutions prepared in order to ensure that the project remains exactly on the timeline and within the planned budget.

3.2.3. KanBIM and BIM 5D-related Approaches

In order to optimize the previously described schedule management approaches— particularly the LPS—Sachs et al. introduced the KanBIM method in 2010. In general, the Kanban system describes "*a production control system for just-in-time production and making full use of worker's capabilities*" (Sugimori, Kusunoki et al. 1977). This enables the responsible persons to receive information about the "*production capacity, operating rate, and man power*" of a specific workshop (Sugimori, Kusunoki et al. 1977).

As such, combining the basic principles of KanBIM produces the elaboration of the project's design by 3D BIM, the management of construction work execution in accordance with the LPS, the visualization of the construction progress, and highlights obstacles within the execution workflow by means of Kanban signals and symbols within the 3D BIM (Ballard 2000, Radosavljevic 2007, Sacks, Radosavljevic et al. 2010).

The innovation to use virtual 3D BIM/CAD models in order to represent project performance was initially suggested by Songer et al. (2000), who investigated workflow modeling's relationship with virtual 3D modelling to visualize project performance and, moreover, the current state of work execution on-site (Songer, Subramanian et al. 2000). Later developments have applied the 4D method, which connects the virtual 3D model with time-related activity information (Bansal and Pal 2008). Further common approaches have added the cost factor in order to improve the virtual 3D CAD model by including the appropriate project cost elements alongside project-related time information (4D). This method is commonly referred to as the 5D BIM methodology, as described in the introduction chapter of this thesis (JOCU 1985, Fan, Wu et al. 2015, Sánchez-Rivera, Galvis-Guerra et al. 2017). Figure 17 provides an (process chart) example of the 5D BIM approach, whereby the individual 3D model objects are manually allocated to the corresponding cost positions as well as schedule activities.

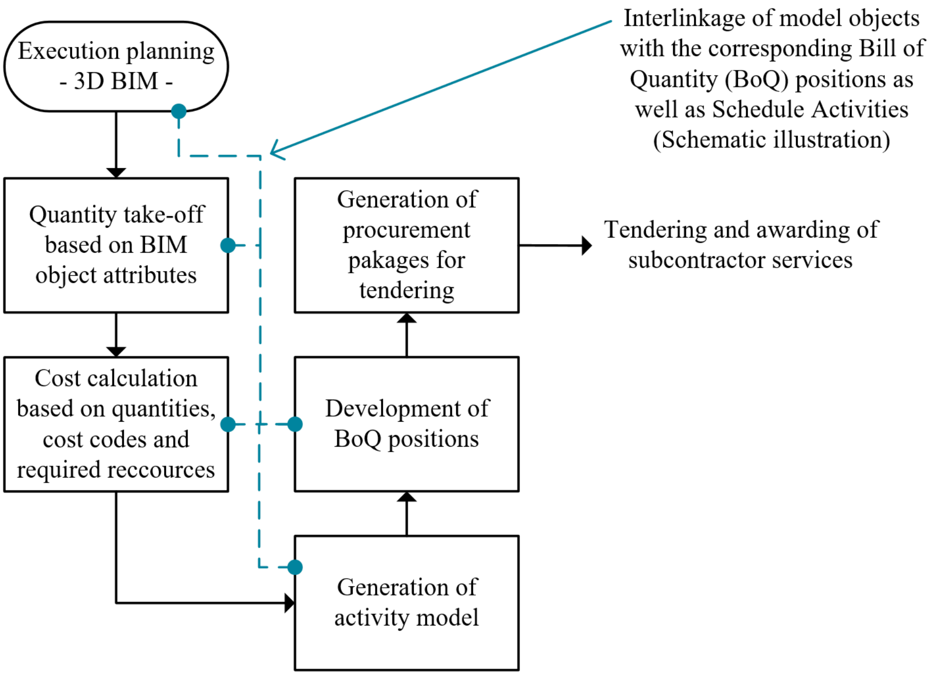


Figure 17: The 5D building information model (5D BIM) approach - the figure shows the 5D BIM process with a schematic illustration of the linking element (blue dotted line).

To assign work execution tasks to specific project model objects, Sacks et al. proposed using fine-grained activity information from a 3D model and creating work packages, which can be split into trade-specific tasks that are manageable by individual workers. These packages are represented within this model by Kanban symbols or as a group of highlighted objects (Sacks, Radosavljevic et al. 2010). Each contractor has to develop an individual trade-specific weekly work plan, which is later synchronized with a general (project-wide) weekly work plan. The “Kanban card type pull flow control signals and Andon alerts” display the constraints and workflow interruptions within the 3D model (Sacks, Radosavljevic et al. 2010). To avoid interruptions to the execution process, daily on-site inspections and adjustments are conducted by a team of trade-leaders, foremen, and site managers. The actual project performance statuses are displayed live by the 3D models on various screens at the construction site (Sacks, Radosavljevic et al. 2010).

Although this methodology improves the reliability of task delivery and reduces variability, it also drastically enlarges project management targets, as trade-specific work plans must be developed in a weekly sequence before trade-related tasks can be negotiated due to synchronization with project-wide weekly work plans. In this way, tasks with lower priority negatively affect the decision-making process and encourage undesirable discussions. In this scenario, the highly productive and efficient character of the weekly last planner meetings threatens to disappear. Moreover, a trade-specific and project-wide evaluation and coordination of constraints could cause unavoidable latencies, which are critical for proper performance status indication and may hinder the flow of the project.

3.3. Process Analysis of an Exemplary Project Scenario

3.3.1. System Theoretical Approach

In order to examine the connections and interrelations, a construction project should be considered as a coherent and interconnected system or workflow structure that is constantly influenced by a multitude of internal and external variables and dependent on numerous influencing factors, which in each manner affect the project's time course (Wiener 1965, Baecker 2016).

For this purpose, it is compulsory to explore and describe the fundamental structure behind a construction project workflow concerning important interrelationships within the organism, particularly with regard to the schedule-influencing factors. The investigation and description of the process basically follows the theory of systems (ToS) by Wiener et al. (Wiener 1965). This approach takes into account the whole organism of a process and fundamentally describes how systems work from a construction project perspective, detached from the individual planning and execution phases. The complex structures have to be reconstructed, and thus evaluated, on the basis of a comprehensive process analysis.

Systems could either be open (interact with the surrounding environment) or closed (independent of the surrounded environment). To describe a system, it must be broken down into its individual parts (subsystems). Interconnected and mutually influencing sections must also be disclosed in order to explore the correlations and interfaces between the individual parts and sections (Wiener 1965, Baecker 2016). In this way, the system's principal structure becomes visible and unsuspected connections as well as possible failures can be detected. This is important for understanding the system's basic mechanisms, and it enables justification activities in the first place. In case of a negative or problematic finding, the system's structure runs the risk of being inefficient. The worst scenario that could affect a system involves a series of issues or the occurrence of several unfavorable process characteristics, which mostly cause the overall system to downfall (Willke 2014). Ballard (2000) expressed this as follows: "*When something goes wrong, as it very often does, the entire structure is prone to collapse*" (Ballard 2000).

According to the ToS, operations and interactions between certain parts or sections of the system are commonly designated as *communication*. If communication is successful, this will lead to synergies (*all factors working together in a complementary way*); if not, it will cause entropies (*susceptible to disorder, disturbing the process, difficult to predict*), in accordance to (Willke 2014, Baecker 2016). A quote by Wiener (1965) regarding the ToS indicates that, "*just as the amount of information in a system is a measure of its degree of organization, so the entropy of a system is a measure of its degree of disorganization: and the one is simply the negative of the other*" (Wiener 1965).

For relatively[18] complex systems—as is the case for construction projects—a variety of applications take over internal and external communication tasks in order to organize proper design, stakeholder, supply chain, cost, and time requirements. Following the metaphor described above, according to which the individual process parts "communicate" with each other, the schedule should be seen as the central connecting and communication element.

However, examining daily practice has revealed that, oftentimes, a single, generalized schedule method is utilized to manage a construction project, which is predominately customized to neither the basic structure of the related project nor to its specific process requirements. Once applied, the (often single) schedule method determines how each time-related aspect will be handled during the project's cycle. For instance, if a waterfall-based method is applied, multi-flexible tasks, short-term interventions, or ad-hoc operations cannot be optimally integrated into the project workflow.

Even if both waterfall and multi-flexible methods are applied, an interlinkage between the two methods is often non-existent. Many projects are scheduled during the design, procurement, and execution phase using simple Gantt charts, which are rarely related to each other and only marginally referenced to the real project`s progression. Moreover, it has been found that numerous current construction projects lack a consistent workflow-based connection between

[18] According to Luhmann (2009) the definition of complex systems encompasses mainly self-organized structures, that could not be described comprehensively, pursuant to ordinary mathematical principles (compare to: Luhmann, N. (2009). Einführung in die Systemtheorie, Carl Auer Verlag.).

design, procurement, and execution targets and the applied project schedules. Additionally, an inference operation regarding the *as-is* state and the targeted situation is often missed.

At this point, it is important to note that existing scheduling methods (Gantt chart, line of balance, etc.) should not be criticized in detail, but should rather be evaluated in terms of their applicability to dynamic (flexible/agile) or constant proceeding processes driven by the question of which method best fits which process.

Due to their regular organization, waterfall systems are best suited to projects with consistent or repetitive proceedings as well as recognizable long-term intervention requirements. However, this method features a significant disadvantage in its non-dynamic ability to react quickly to rapidly changing procedures or ad-hoc operations triggered by unpredictable events, which is a common procedure in most construction projects (Echeverry, Ibbs et al. 1991, Tory, Staub-French et al. 2013). As such, multi-flexible approaches are ideally applicable to handle complex, dynamic, and uncertain project conditions. Nevertheless, multi-flexible methods feature deficiencies in their difficulty predicting the project's progression and the lack of transparency in timescale objectives due to the flexible organization of task execution (Ballard 2000, Ballard and Howell 2003, Mossman 2015).

The LPS approach was utilized to replace the rigid and inflexible structure of the waterfall-based scheduling system with the agile approach in order to more flexibly organize construction work execution. With the development and introduction of the KanBIM method, BIM planning was applied in order to enable visualizing the construction work execution and to highlight disruptions within the construction flow using the Kanban Card features in addition to utilizing the LPS to manage construction work execution (Sacks, Radosavljevic et al. 2010). These approaches, individually and in combination, have already led to some notable improvements regarding efficiency and productivity improvement in the projects to which they have been applied.

3.3.2. Project Process Analysis

In order to analyze a project's core structure, it is important to deeply investigate its basic process workflows as described by the previous section. In this way, the system's principal structure becomes visible and unsuspected connections as well as possible failures can be detected. This is important for understanding the system's basic mechanisms and it also enables justification of the activities in the first place. The following graphic (Figure 18) illustrates the course of one currently common construction project workflow[19], including its individual parts (sub-systems) and interconnected sections. Here, it must be stated, that may other possible project workflows could be applied for additional analysis purposes.

[19] Due to international divergent project characteristics, a reasonable basic process of a currently common building project should be assumed.

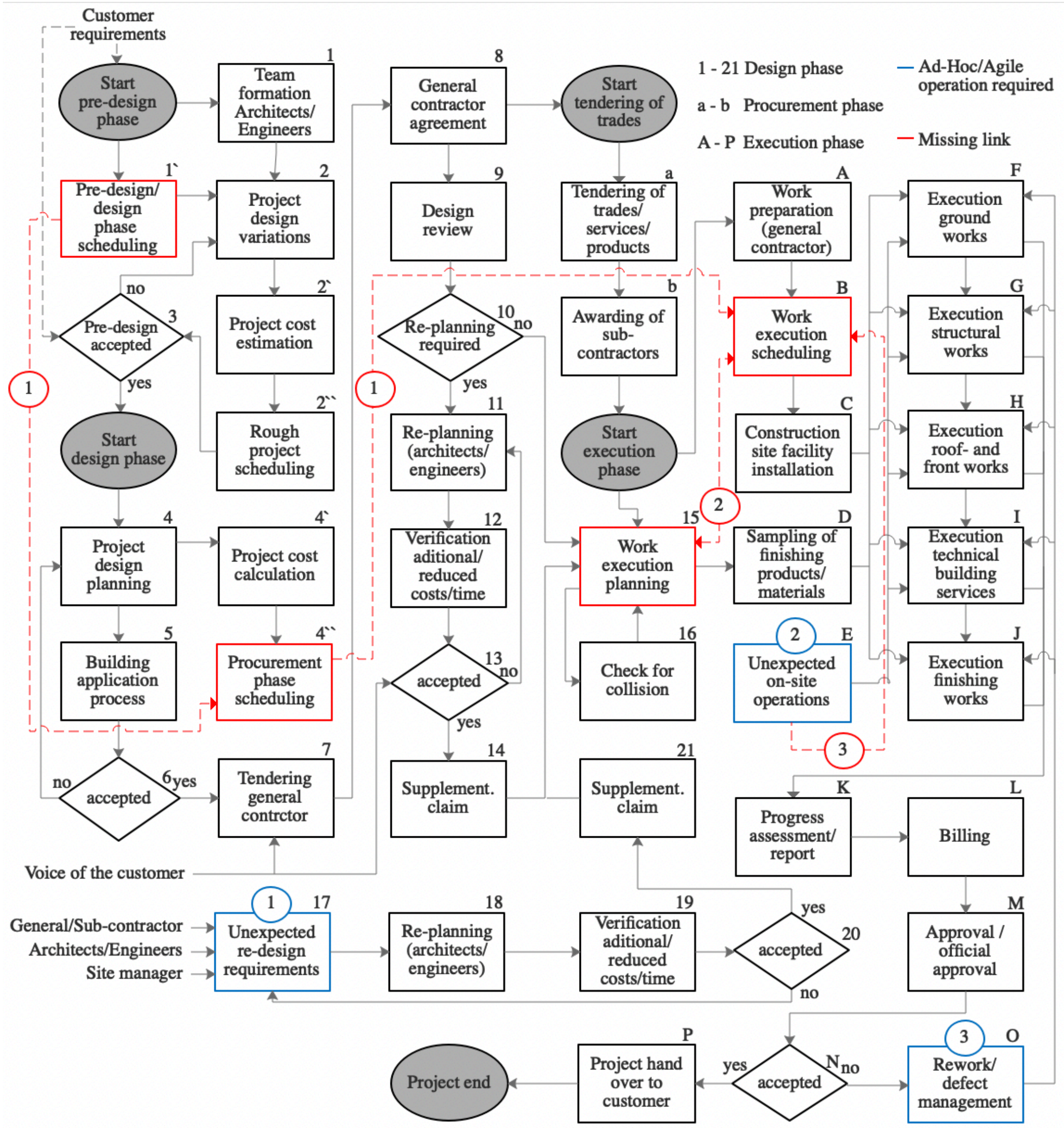


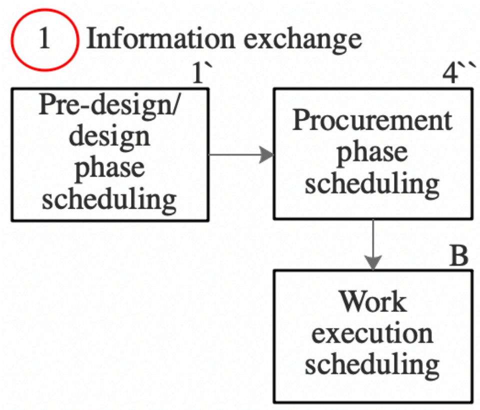
Figure 18: Assumed current construction project workflow and representation of weaknesses within the process chain

Regarding project scheduling operations, the figure above illustrates internal and external influencing factors, which are critical for a coherent and interconnected project workflow. Missing but important workflow connections and insufficient information feedback loops—highlighted in red—impede crucial project performance indications by preventing appropriate reactions to impending postponements. Moreover, the flowchart displays a high incidence of multi-flexible or ad-hoc process activities—marked in blue—which cannot be optimally organized by a waterfall-based schedule method.

In order to improve the overall structure of the provided process chart, the entire structure must be analyzed and modified to become a proper and coherent system. This could be achieved by following the methodology of Shewhart`s plan-do-check-act[20] cycle (Ballard 2000). A detailed description of the specific structural issues, that have to be improved is listed under Table 1:

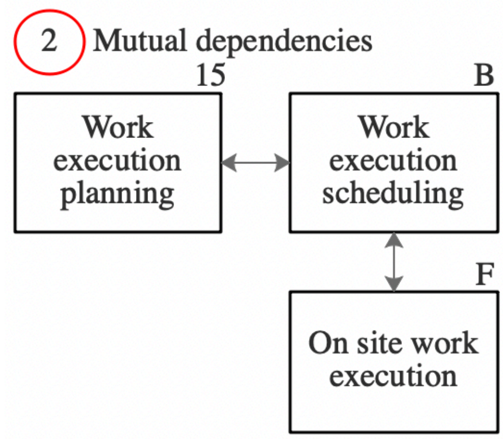
Table 1: Structural deficiencies in currently common construction process workflows

<u>Unrelated/uncoordinated schedules</u>



A common substantial mistake occurs due to independent, discontinuous establishment of the design, procurement, and work execution schedules. It is unlikely that postponements are considered and accordingly compensated during a project.

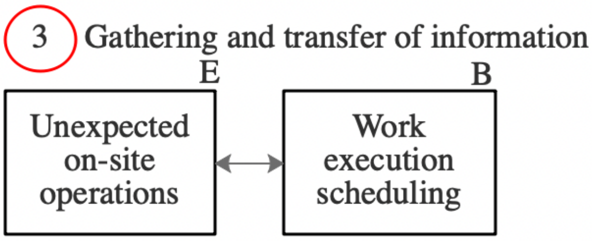
<u>Missing interconnections between project design, corresponding schedule activities and on site operations</u>



Project design objects and related schedule operations are often only loosely connected to each other. As such, changes in design produce no direct influence on schedule operations in order to restructure the on-site execution sequence

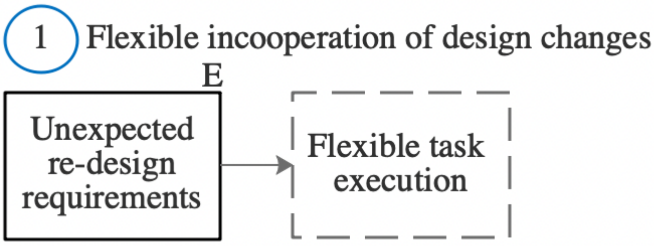
[20] The cycle was made popular by W. Edwards Deming, thus it is often referred to as the Deming-Cycle.

Tracking and scheduling of ad-hoc on-site operations



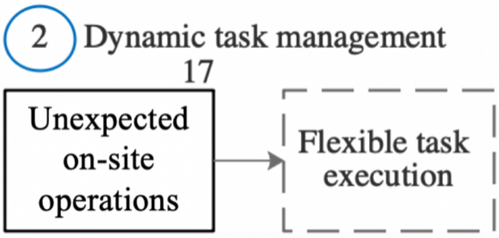
Ad-Hoc on-site operations are rarely tracked or managed by the work execution schedule. They have no influence on the planned construction targets and do not postpone any of the ongoing or open tasks. Thus, the flow of the project`s execution is often disrupted as common a consequence.

Inflexible schedule tools and outdated schedule statuses



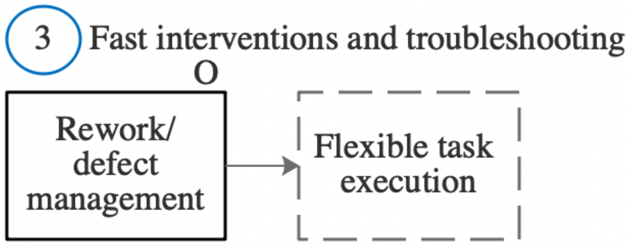
Required ad-hoc operations on site are not synchronized with or managed by the project execution schedule. In this way, the short-term task organization on site is handled without any clear structure.

Postponements due to rescheduling



Impediments during a project's design as well as changing customer requirements contain potential for re-planning, which often causes schedule delays. Due to the assumed independent character of the design schedule, direct impacts (postponements) to the procurement and work execution schedules are not automatically triggered.

Late responses to unpredictable impacts



Changing project conditions produced by customer, stakeholder, or regulation demands increase the risk of re-planning and re-work activities. Additionally, rejected trade approvals increase the demand for a fast and flexible re-work performance. Therefore, an agile task organization is required.

The table above illustrates potential weak points and missing interconnections that are critical to a coherent and interconnected workflow. Of particular importance is the fact that a comprehensive restructuring and improvement of construction management in general, as well as successful and precise schedule and cost control, can only succeed if the entire process of a construction project is under consideration.

Beside the demonstrated weaknesses, some important factors retain considerable potential for significant improvements, though they have to date been widely disregarded. It can even be argued that a holistic method appropriate to the different challenges of the complex construction project requirements has not been developed so far. As such, the necessary but yet missing key specifications are summarized under the following points:

- Close cohesion between predesign/design information (3D model objects) and project-related time and cost values could be achieved via a tight interdependence between the 3D model objects, the corresponding bill of quantity positions (costs), and appropriate execution durations (time).
- By using the early division of the 5D BIM into clearly defined project sections (PSs), the determination of executing relevant target dates could provide a basic grid, which is necessary to structure the multi-flexible-organized project execution.
- The actual required resources and values determined during work execution (e.g., the actual required execution durations of specific tasks/actual used resources, etc.) could be compared with the planned values.

- An information feedback loop could be implemented in order to report back deviations between planned and actual required values. On this basis, continuous improvement strategies could be implemented, thus contributing to sustainable improvements of the planning accuracy of future projects.

As mentioned at the beginning of this section, the following figure presents an exemplary construction design and execution process that is considered common and widespread in the construction sector (Figure 19). The overall process should be examined and analyzed regarding weaknesses and potential for improvements in accordance with the enhancement of schedule reliability and precise cost management. Its basic structure comprises a 3D CAD model and, besides the tendering and contracting of subcontractor services, also features a waterfall-based organization of the work execution. The overall process is characterized by its appropriate process steps, illustrated in Figure 19 below:

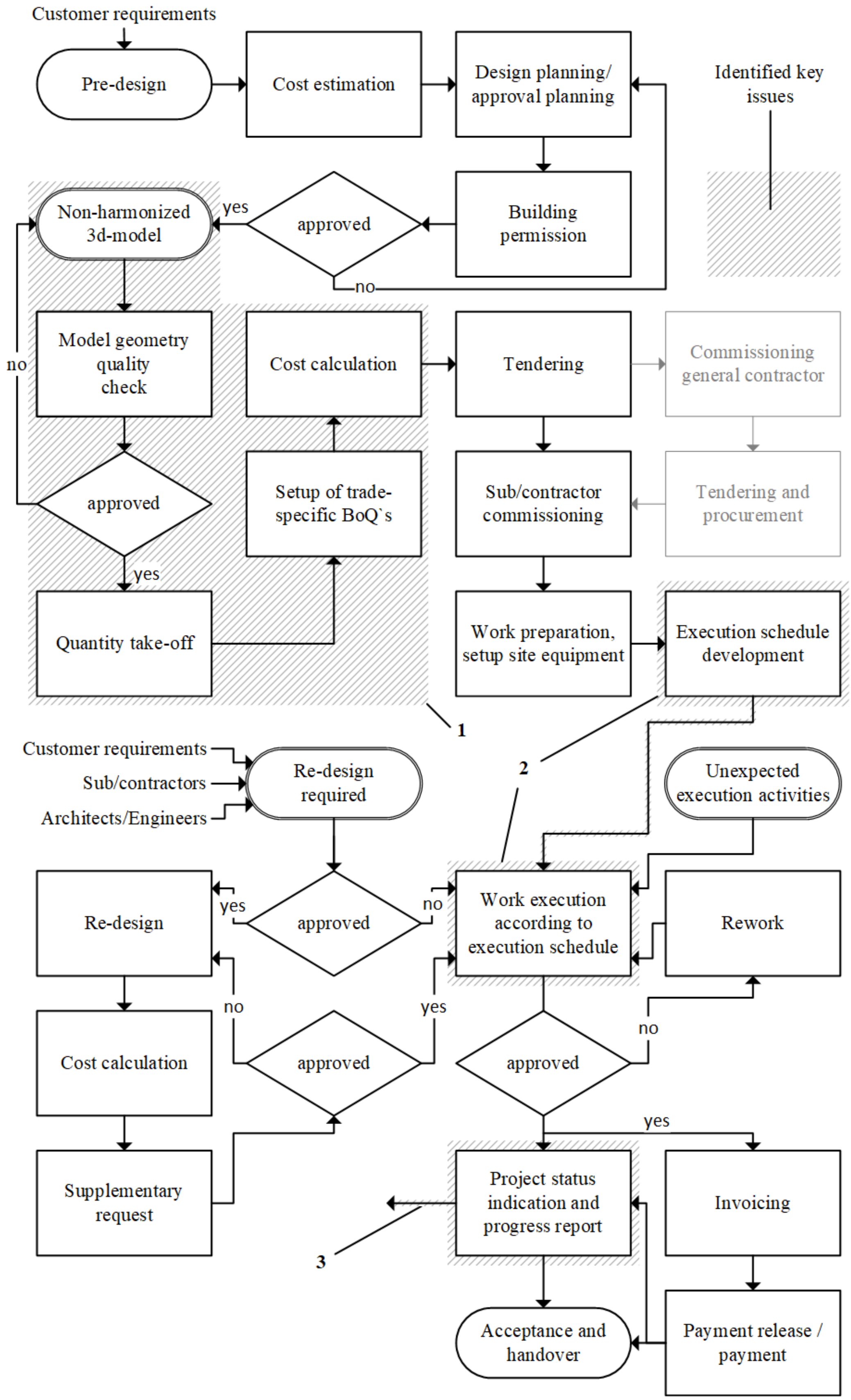


Figure 19: Potential enhancements within currently common construction process workflows

The options to improve the overall process of a currently common construction project are represented below:

1. The significant issues include a missing interconnection between the individual 3D CAD model objects/elements, appropriate schedule operations, and the corresponding BoQ positions. In addition, the construction process sequence is not enhanced or optimized by simulation. Therefore, the project design, project costs, and execution time threaten to drift apart over the course of the project, which will impede project control and is critical to project success.
2. A detailed development of the work execution schedule often takes place immediately before the execution phase starts. Moreover, utilizing a slightly flexible waterfall-based scheduling method appears inadequate for the numerous unexpected and unpredictable on-site incidents. Additionally, permanent cooperation between the work execution schedule and on-site operations is required.
3. Significant deviations between the planned and used recourse values could be reduced by implementing specific information feedback loops, which report back crucial as-built values/information (Ballard 2000).

4. Problem Statement

After the literature study has been carried out, it can be stated that a large number of studies have already dealt with the subject areas of productivity and efficiency in the construction industry. Numerous general as well as specific reasons for the slow progress have been identified. Many general but also very specific reasons for the slow progress were identified; hence, inadequate construction management, difficulties within the construction process organization, or the inefficient execution of construction work were considered as basic causes for the weak growth within the construction sector. Furthermore, amongst others, difficulties due to insufficient precession during construction planning, delayed supply of planning documents, continuously changing project partners, or the lack of project partner's commitment to a specific project are mentioned as decisive factors (Howell, Ballard et al. 2011, Larsen, Shen et al. 2016, Oesterreich and Teuteberg 2016). Additionally, the investigation has indicated that ongoing and frequent delays of construction schedules as well as deviations between planned and actual required costs, can be ascribed to the initially stated reasons (Teicholz, Goodrum et al. 2001, Publications-Office-of-the-European-Union 2003).

Critical analysis of the familiar and applied construction management approaches revealed that, although implementation of these instruments possesses far-reaching optimization potential, the methods are used inadequately or are not optimally aligned with process requirements of the respective projects. Additionally, insufficient tracking of timelines and cost control by the assigned personnel in the projects were identified. Often only one schedule method or management approach is used to control and manage an entire project, or even just individual project phases. An example would be the LPS, which describes a supportive approach for coordinating and organizing the building construction per agile method, although was developed exclusively for the purpose to manage construction work execution (Ballard 2000). However, the use of this method is recommendable due to its ability to address the numerous, continuous, and unforeseeable circumstances which occur on the construction site; but it does not apply the planned construction effort values determined during the design phase. Thus, it became clear that the vast, highly complex, and continuously growing demands entailed by projects in the construction sector cannot be handled or solved holistically in this manner.

The investigation and evaluation of productivity growth during the past two decades has revealed that development and implementation of many novel and innovative approaches, such as BIM, the LPS, or the lean construction principles, have just resulted in a marginal incensement of the productivity values and in efficiency optimization within the construction industry. Considered separately, the methods and technologies enable several opportunities for optimized working methods; related to planning, management, and control of an entire construction project, and over all execution phases, there are only a few stand-alone solutions. This includes combined methods such as the KanBIM approach, which has yet demonstrated improvements in project performance, in addition to an increasement of the productivity rates of finished construction projects; but, due to enhanced features and new technological options these methods run out of date. The intensive analysis and evaluation of the processes of currently used construction project workflows has also shown that essential links within the project phases are still missing or need to be optimized. The construction schedule is often not used as a control tool for the timely completion of the construction work. In addition, a target/actual comparison, which provides information about planned and actually required execution times during execution or after completion of a construction project, often remains unused.

Despite the described, multifaceted weaknesses within today's construction planning and execution processes and the already developed and applied schedule planning tools as well as construction management approaches, it seems that the development of a holistic method that considers the entire process of a construction project and achieves sustainable improvements and overall optimization of the above-mentioned problems has not been achieved so far.

Consequently, based on these findings, the following enumeration summarizes the problem statement, in order to set the foundation for the development of a comprehensive solution approach:

- previous construction planning and execution organization methods were found as not sufficient
- essential links between design, costs and construction time are defective or non-existent in the overall processes of current construction projects
- a consistent flow of information along the various project phases is not necessarily ensured

- the use of waterfall-based scheduling, which has been used to manage construction execution to date, does not provide the critical flexibility that is essential for the complex and constantly changing conditions on the construction site
- the implementation of a continuous improvement process is rarely used in the overall process of today's construction projects

These difficulties contribute to the persistent overruns of construction schedules as well as budgets of today's construction projects and lead to an underutilized project performance and moreover to an insufficient project outcome.

5. Hypothesis and Solution Approach

5.1. Hypothesis

The issue of insufficiently implemented or applied construction project management methods and the lack of organization approaches to achieve the maximum possible success in schedule control, has made it inevitable to develop a holistic system that offers an all-encompassing solution. It can be assumed that the approaches investigated and critically examined so far, taken together, offer sufficient potential to completely eliminate the identified weaknesses that currently arise during the implementation of construction projects. If the already presented technological, IT-based and strategic innovations for construction management and schedule organization are combined in a system, where the respective requirements of the individual construction phases and process steps are optimally addressed and accomplished, it can be postulated that considerable improvement with regard to schedule and cost adherence as well as the overall project performance can be obtained - provided that the construction projects are completely implemented according to this method. In addition to these optimizations, a continuous and sustainable adjustment of the cost and schedule-related effort values required for future planning can be expected on the basis of a continuously performed target/actual control and feedback of the actually required values.

5.2. Solution Approach

In order to fulfill the expectations of a holistic and comprehensive method to sustainably optimize schedule reliability and organization enhancement of future construction projects, it is necessary to combine several relevant construction and project management strategies. In addition, features with regard to the individual process requirements as well as specific workflow demands must be implemented accordingly. During the construction planning phase, a fixed interconnection of the planning elements with the corresponding construction time and cost values in accordance with the 5D BIM method is indispensable in order to prevent a drift apart of the design objects, as well as the construction time and costs elements.

Additionally, it must be ensured that the current design status is available at the construction site constantly, and on time in order to prevent construction work from being carried out according to old design statuses and to keep the construction process in an optimal flow. For this purpose, the 5D BIM should be implemented as a so-called Single Source of Truth (SSOT) in the overall process, from which all information emanates and by which the current status of the construction work is also represented.

It is also important that the construction schedule is already developed during the planning phase and established as a leading structure in the overall project. Planning schedules as well as procurement schedules should be linked to the construction schedule.

In order to achieve an multi-flexible construction process, important project milestones as well as the start and end of construction must be explicitly defined during the project design phase. This can be achieved by planning the construction process with already known time expenditure values, using the waterfall method. Subsequently, the 3D BIM objects should be linked to the corresponding schedule activities and cost items, in regard to the 5D-BIM method. Thus, the 5D model offers the ability to simulate the construction planning sequence in conjunction with the respective execution times and associated construction costs. The simulation procedure is also used to optimize the planned construction schedule. Of particular importance is the determination of significant project milestones, as well as the execution start and end date.

A following step is the tendering and awarding of the subcontractor services, before the construction work can be conducted in accordance with the agile method, in order to ensure maximum flexibility for the execution of the construction work. To ensure that the progress of the project can be continuously compared with the open task list with regard to the next upcoming project milestone, periodic previews and reviews are implemented, in order to achieve a proper execution organization.

Furthermore, as by the KanBIM method proposed, special importance is placed on the representation of the current construction progress by highlighted model objects of the 5D BIM (Sacks, Radosavljevic et al. 2010). Moreover, it is essential that the actual used resources on site are determined and compared via target/actual comparison with the planned recourse values. Deviations between the planned and actually required values can thus be identified and reported to the planning department accordingly. In this way, relevant effort values can be continually optimized and reused for future project planning. In this way a continuous method for improvement can be implemented by adjusting and refining the time as well as cost values of future construction projects.

This package of measures thus offers a comprehensive and holistic solution approach and contains substantial optimization potential regarding the identified and analyzed possible vulnerabilities of schedule and construction management approaches identified so far.

6. The 5D-PROMPT Method

6.1. Theoretical Process Description

To fundamentally change the aforementioned impediments and achieve pervasive improvement to the overall project performance as well as schedule and cost reliability for future construction projects, the following paragraph introduces a holistic construction planning and project management method. This novel approach consists of the 5D-PROMPT method (where the acronym PROMPT stands for Process-Related Organization Maintains Project Timelines). Here, 5D is derived from the term for the fifth dimension of construction planning, which encompasses a three-dimensional, virtual building information model (3D), the linked time effort values (4D), and corresponding construction costs (5D; Tanyer and Aouad 2005).

This chapter addresses the development of the method schematically and as a theoretic process to explain the mechanism and internal connections of all required process steps. Following this, the method's implementation and practical application is described using a comparative case study to test and analyze the applicability and possible improvement potential of the new method compared to an approach used so far. The planning and management structure features the entire planning process and all execution phases of a construction project, including those from the architect/planner side and from the contractor/subcontractor side. Special importance is placed on drafting the design according to the 5D BIM method. Here, the tight interconnection of the construction design planning (3D BIM) with the time (4D) and cost-based (5D) effort values are critical.

Beyond this, the direct connection between the construction planning phase and the work execution phase is of utmost importance. It is crucial for the overall process to implement the 5D BIM as an "SSOT" where all information (quantities, costs, execution times, current planning status, etc.) can be deduced. Furthermore, the current status of the execution is represented through a color-coding of model objects by the same 5D BIM. A further difference of the 5D PROMPT method compared to conventional methods concerns also the specific timeline management along the projects progress. During the design phase, the construction sequence is initially planned as a theoretical project structure plan and is developed in accordance with the waterfall method. On this basis a construction sequence schedule is developed and tested via simulation and optimization. This process enables scheduling of the construction work during the planning phase on the basis of a well-known and familiar procedure. Subsequently, significant project events (as project start/end date as well as project milestones) are determined during the 5D simulation process. These events set the outline structure for the later conducted multi-flexible-based work execution on site.

Hence, the process features a complete transformation of schedule organization which is initially based on waterfall-based scheduling and turned into agile work execution organization. The present work focuses on this point regarding the theoretical visualization and explanation of the 5D PROMPT method. The transfer of the construction plan’s time-based information is thus just manually processed. To avoid extending this study’s scope, a fully automated process for transferring the specific schedule information from the Gantt chart into the execution-planning-board structure should be developed and tested in a future study.

To transmit the schedule information, it is important that significant events, such as construction start and completion dates, as well as relevant project milestones (e.g., completion of a level or a building unit), are transferred and utilized as a foundation for multi-flexible execution organization. This measure ensures that the construction schedule can be planned and optimized on the basis of the determined model quantities in connection with the associated cost and time effort values. Thus, a basic structure for the agile execution organization can be implemented on this basis, which guarantees the required flexibility for unpredictable hazards or ad-hoc activities during work execution on site.

For sustainable optimization of construction design and project execution, as well as to ensure cost and schedule reliability of future construction projects, crucial insights from the construction work phase (target/actual comparison between planned and actually required construction times, quantities, costs, etc.) have to be considered and reported to the planners in the final step of the 5D-PROMPT method. Hence, frequent adjustment of relevant effort values for future planning will help to minimize deviations between construction planning and execution. Furthermore, this measure leads to the initiation and permanent implementation of a continuous optimization process, which serves as a foundation for sustainable optimization and adjustment of planning and calculation data. The essential steps of the 5D-PROMPT method are visualized through graphical symbols in Figure 20 below in order to illustrate its fundamental mode of operation:

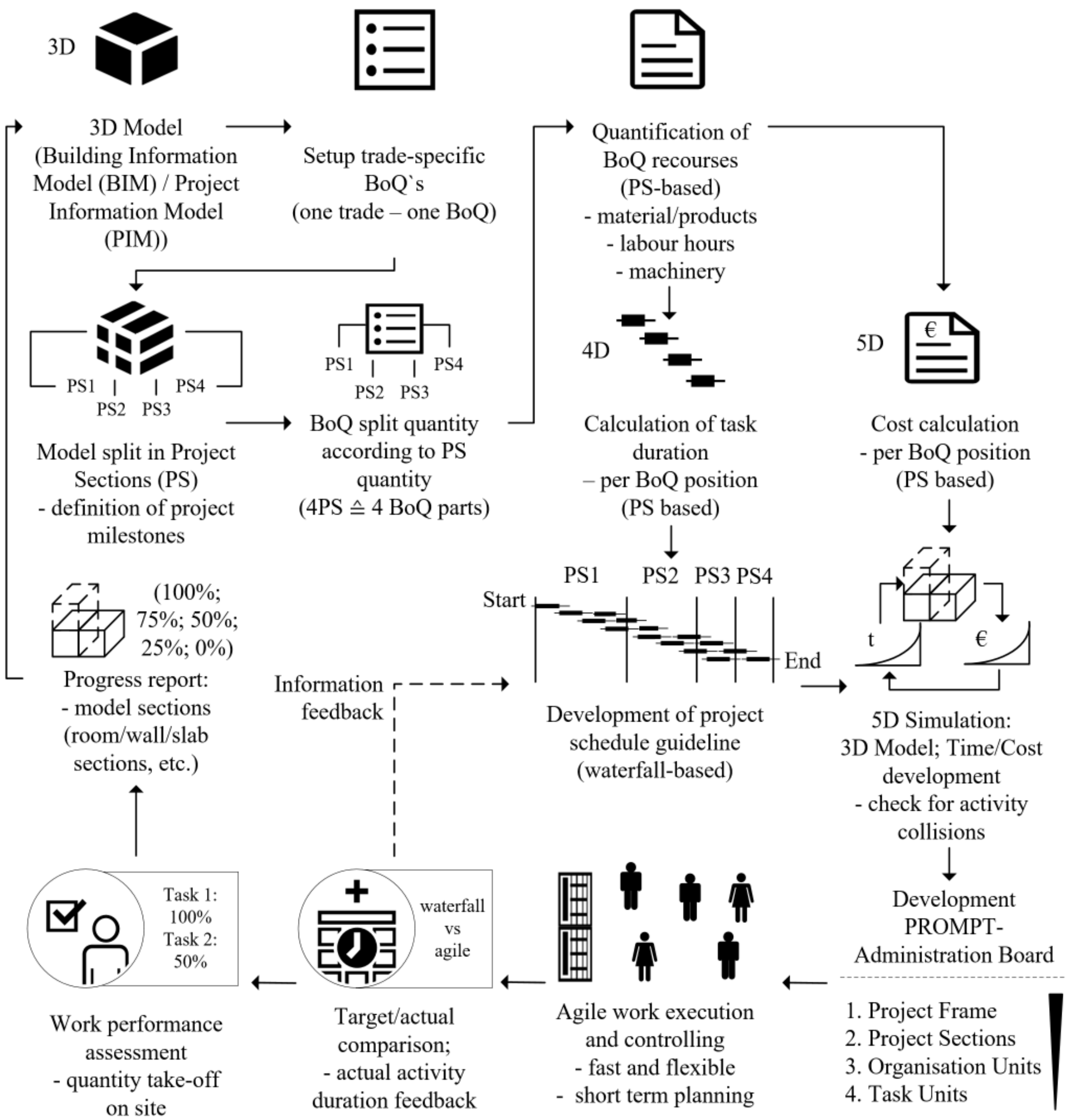


Figure 20: Representation of the key characteristics of the 5D-PROMPT method

The schematic 5D-PROMPT method workflow presented above is comprised as follows:

- Fully applied 5D BIM planning approach
- Virtual construction process simulation / optimization (waterfall-based)
- Determination of project start/end date and significant project events
- Setup of an agile structured project execution planning board
- multi-flexible organized work execution
- Determination and evaluation of the as-planned / as-built data
- 5D BIM-based progress status indication (highlighted by model objects)

Based on the previously presented workflow, Figure 21 below presents the key enhancements and general operating principles of the 5D-PROMPT method:

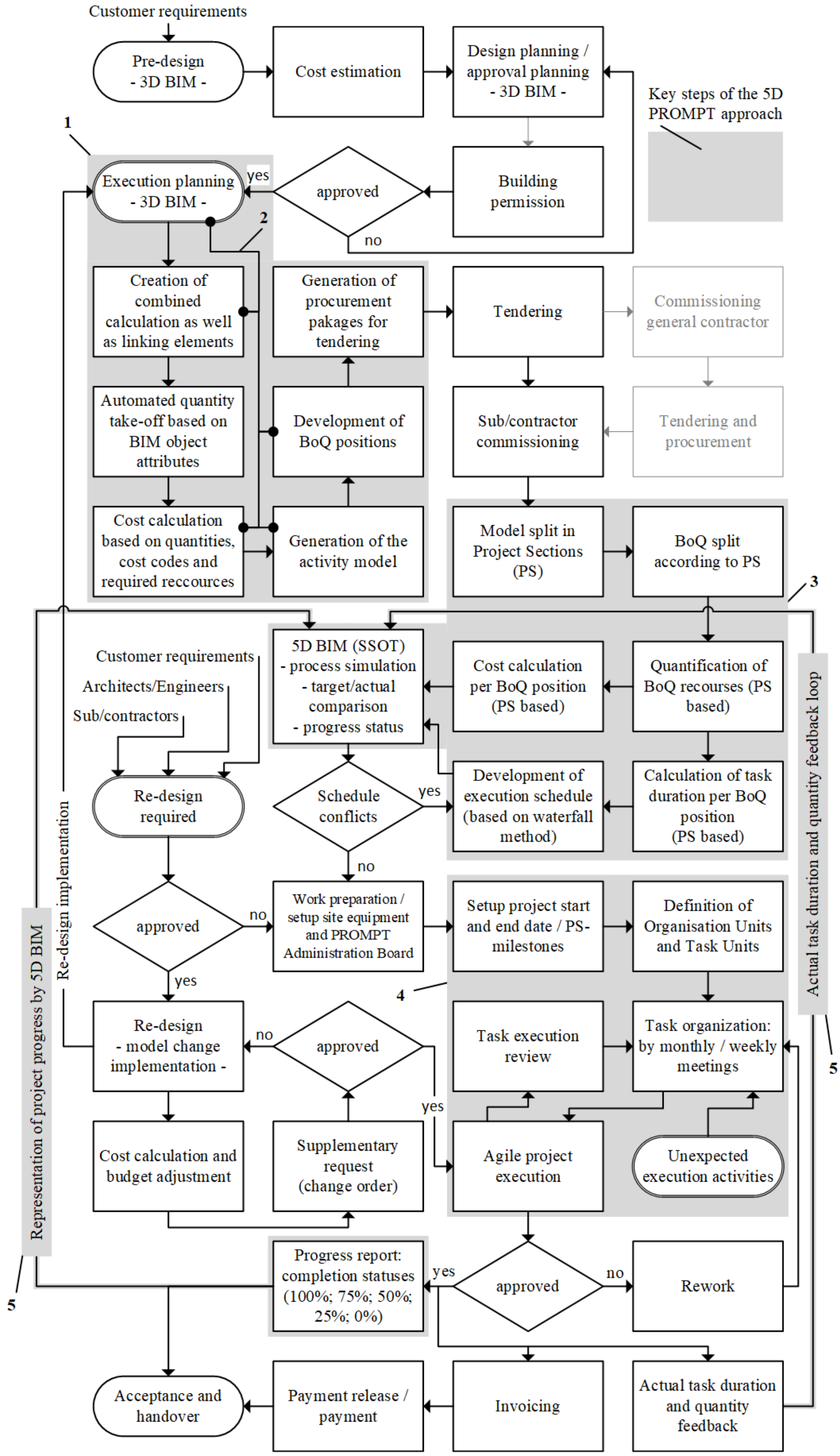


Figure 21: Process chart of the 5D-PROMPT method

The main process steps and technical modes of operation for the 5D-PROMPT method are presented through the marked gray fields in the figure above and are described as follows:

1. Fully applied 5D BIM planning process.
2. IT-supported connection of the 3D BIM objects with the associated BoQ positions as well as schedule activities by utilizing linking elements.
3. Early determination of project duration and Project Sections (PSs) and definition of target dates for PS deliveries.
4. Agile project execution organization according to predefined target dates.
5. Intermediary information feedback loop implementation for project status indication and target/actual comparison via 5D BIM as the SSOT.

The special characteristics of the process steps are described and explained in detail in the following sections. At this point it should be pointed out that this method is partly composed of already existing individual approaches, which however in the presented way enables a new, optimal and sustainable improvement of the adherence to schedules and costs and thus can comprehensively contribute to the success of a project and the sustainable optimization of the basic planning data.

6.2. The 5D BIM Approach

6.2.1. BIM-based Project Design and Allocation of Relevant Attributes

The first part of the complete process refers in particular to the services of planners (architects, specialist engineers, etc.). Beginning in the early stages of planning—exemplary: design phase two (LPh 2) in accordance with the current policies of the German regulation on remuneration for services provided by architects and engineers (Verordnung über die Honorare für Architekten- und Ingenieurleistungen [HOAI][21])—a basis has to be established for linking the design model objects with the related cost effort values and construction activities. This approach is required for the entire construction planning and is applied to all planning phases with their respective Level of Details / Level of Geometry (LoDs).

At this point, it has to be stated, that the optimal application of the 5D-PROMPT method essentially requires an overall project design based on the Building Information Modeling methodology. The processing of the model data with regard to the 5D method uses alphanumeric data (attributes) in addition to the geometric model information; these attributes are required for a later conducted quantity takeoff as well as query of model objects within the BIM. The following figure shows the process approach for creating the 5D model based on 3D BIM planning (Figure 22):

[21] Verordnung über die Honorare für Architekten- und Ingenieurleistungen. Ursprüngliche Fassung vom: 17. September 1976; (BGBl. I S. 2805, ber. S. 3616); letzte Neufassung vom: 10. Juli 2013; (BGBl. I S. 2276); Inkrafttreten der Neufassung am: 17. Juli 2013; Geltungsbereich: Bundesrepublik Deutschland.

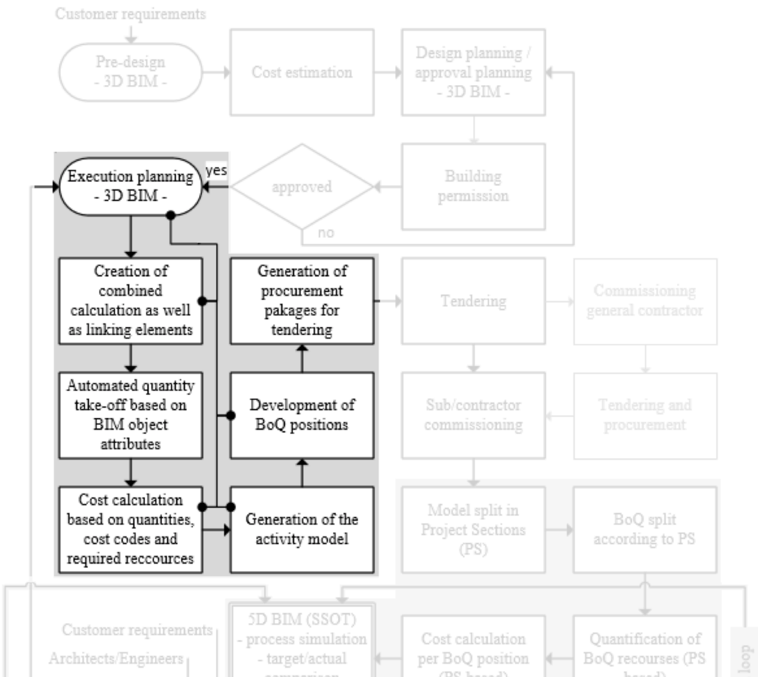


Figure 22: Initial step of the 5D-PROMPT method: Implementation of the 5D BIM approach

When creating the Building Information Model, the respective modeling guidelines of the applied BIM software must be observed. Moreover, with regard to a homogeneous use of the BIM attributes it must be ensured when generating/designing the models that the corresponding attributes are applied in agreement with all project participants. If this is disregarded, it may cause significant impediments between the project participants about the allocation of the used attributes. In order to ensure uniform attribution, the application according to *VDI Guideline 2552 Part 4:2020-08 - Building Information Modeling Requirements for Data Exchange* is recommended so far (Verein-Deutscher-Ingenieure-e.V. 2020). The allocation of the required attributes is assigned to the model objects during the design process of the BIM. This procedure can vary depending on the utilized software solution.

The following two figures (Figure 23 and Figure 24) present examples of the attributes connected to a wall as well as a column element in the modeling software "Revit." The figures were adjusted and revised as per the described application to ensure a better understanding.

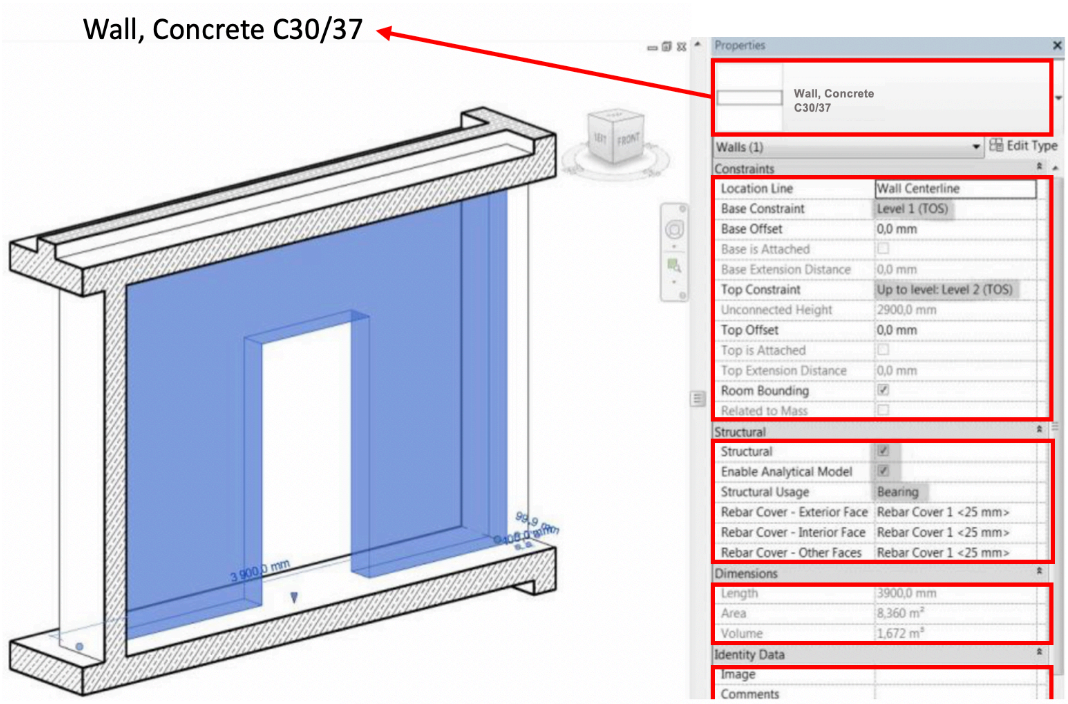


Figure 23: Revit structure modeling example: Wall; representation of the corresponding attributes (Engipedia-BIM-Consulting 2020)

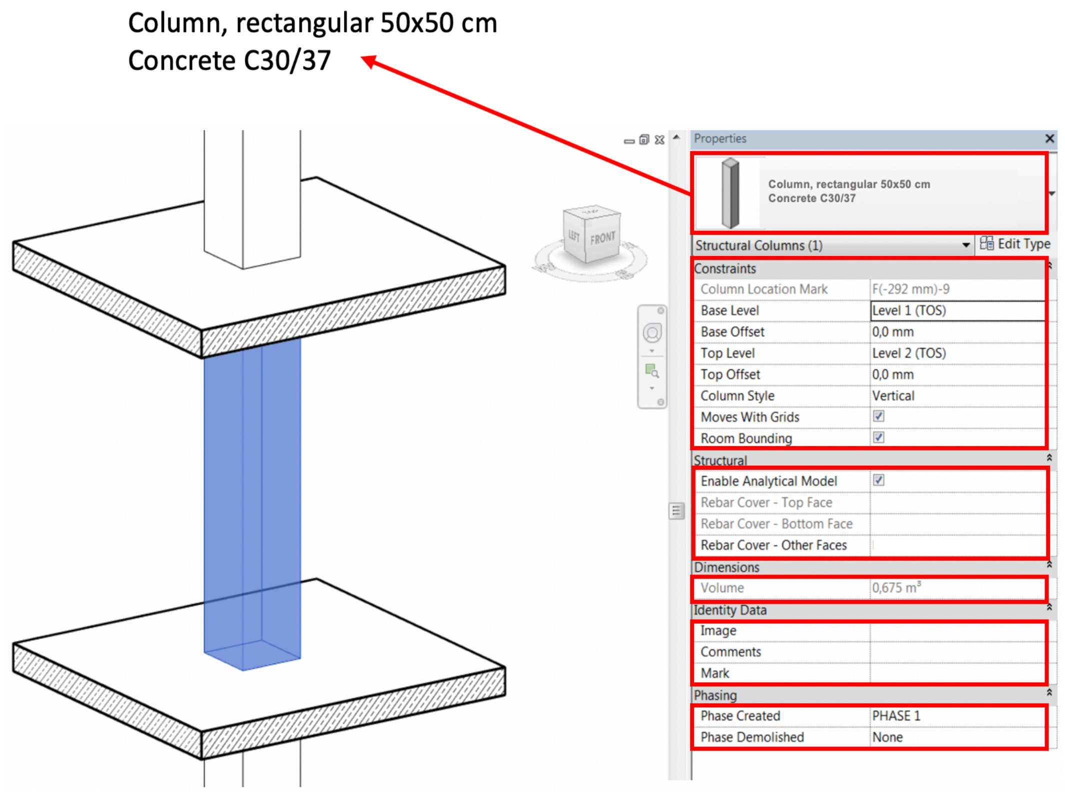


Figure 24: Revit structure modeling example: Column; representation of the corresponding attributes (Engipedia-BIM-Consulting 2020)

Each attribute contains characteristic information regarding the corresponding model element. In the figures above, the attributes under the category "dimension", for example, illustrate the values for length, surface, or volume of the respective model object. With the defined attributes of a model object, every model element can be determined explicitly and filtered through specific filter settings. As a BIM represents the sum of all model elements, single elements or composed element groups can be addressed through the attributes (Figure 25).

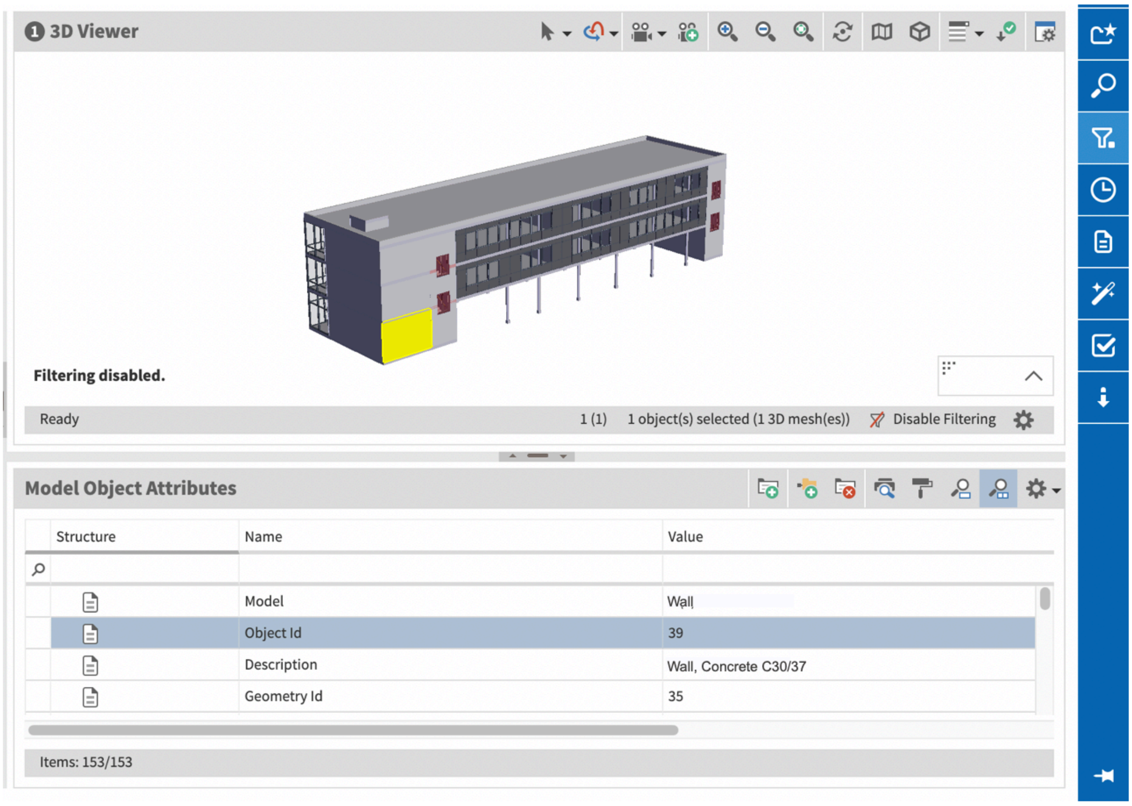


Figure 25: Example: Building information model; selected model object: Wall, Concrete C30/37 - *the BIM was provided by Technische Hochschule Mittelhessen; Germany*

Furthermore, the values of these attributes can be selected with specific software solutions and utilized accordingly during the following process steps, as described within the following chapter.

6.2.2. Software Solutions to Create 5D Models

When the model is completed as per the planning phase requirements (in Germany based on the HOAI-design phases), processing under the 5D method can begin. Here, the model elements are linked with the related time and cost positions using an appropriate software solution. The composition of elements can range from single specific elements up to large construction systems.

It is recommended to use the “iTWO 4.0” software platform from RIB Software SE for the 5D-PROMPT method application, as this software represents the only solution to link the model elements properly and fixed (with a linking position) with the related time and cost positions. Additionally, this software solution enables an automated, model-based quantity takeoff (QTO).

However, it must be stated, for the conduction of the comparative case study, which was carried out after the development of the new method, the RIB software solution "iTWO Baseline 5D" had to be used, as essential modules of the iTWO 4.0 platform had not yet been released for use in practice due to the status of development at the time the case study was conducted. This software version generally differs from the iTWO 4.0 platform, with respect to the requirements of the 5D-PROMPT method, in the way that above-mentioned interlinkage of the model elements with the BoQ/schedule items have to be made manually. In addition, the iTWO Baseline 5D version does not allow a fully automated, model-based quantity takeoff. However, both software systems use a similar set of fully integrated application modules, in order to

- process 3D BIMs, which support model-based QTOs,
- bill of quantities, and
- to develop schedules, which are based on a Gantt chart structure.

Beyond the recommended software solution, it is also possible to perform the application steps of the 5D-PROMPT method with alternative software solutions, but it must be ensured that all model elements, quantities, and the related BoQ positions and schedule activities are manually interconnected; the drifting apart of the individual elements must be urgently prevented at this point. Moreover, the 5D-based construction work simulation may be significantly reduced; hence, optimization of the construction process might become even more difficult. In addition, the model-based visualization of the current construction work status must be conducted manually. Thus, these measures can limit the new method’s performance considerably.

6.2.3. Objective and Explanation of the Line Items

As an essential component for the creation of the 5D model within the software-solution iTWO 4.0, a central element is applied, which is responsible for the linkage of the individual model objects, and the allocated time and cost values. It is called *Line Item* (referred to as Line Item in the following) and was developed by the software developer RIB Software SE[22] in the course of the development of the software platform iTWO 4.0. The functionality of the Line Item is explained by Figure 26:

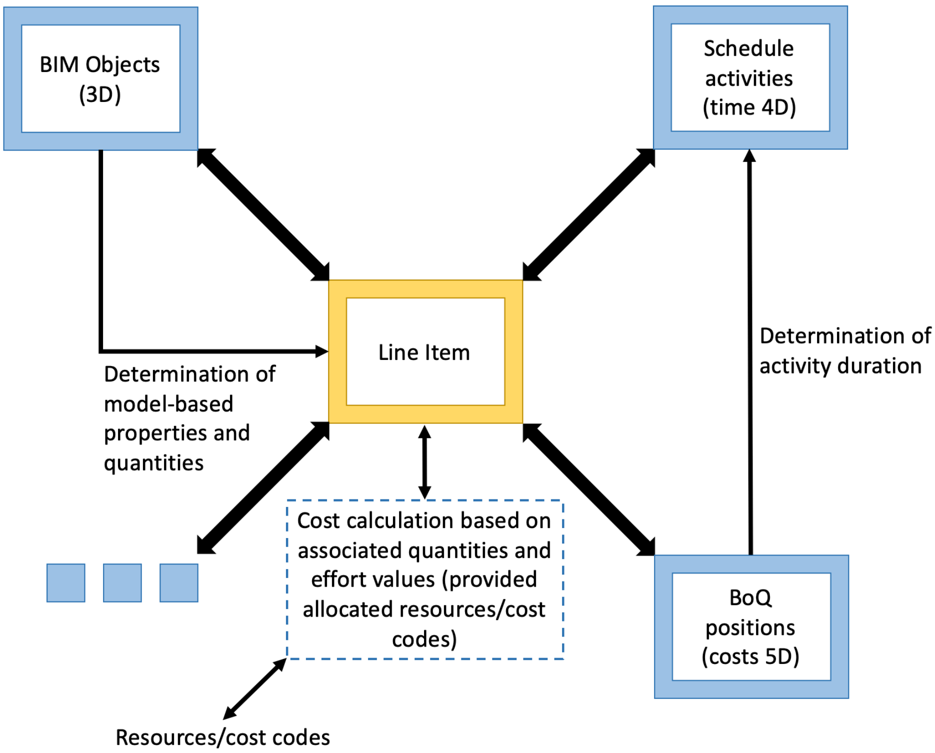


Figure 26: Schematic representation of the interlinkage between BIM objects and its corresponding time and cost positions[22]

The Line Item is generally considered as a calculation item, since the cost calculation of the construction targets are created on the basis of this item; however, in the applied 5D methodology, it represents the central linking element, that can perform a number of different connection functions.

[22] Copyright by RIB-Software SE; Vaihinger-Straße 151, 70567 Stuttgart.

The Line Item contains beside the description of the construction targets—derived from the 3D BIM—also the quantity and corresponding Unit of Measurement (UoM) of the allocated model objects. To calculate the construction costs, the derived model quantity is multiplied by the values of the assigned cost elements (resources required to perform the construction services - labor, materials, equipment, subcontractors, etc.). The cumulated result of the cost calculation aims in the construction costs of all services. On top of each cost position a general or specific markup has to be assigned, in order to achieve the sum of the overall construction costs of the entire project. The following graphic shows the example of a Line Item with the corresponding effort values on which the cost calculation is based (Figure 27):

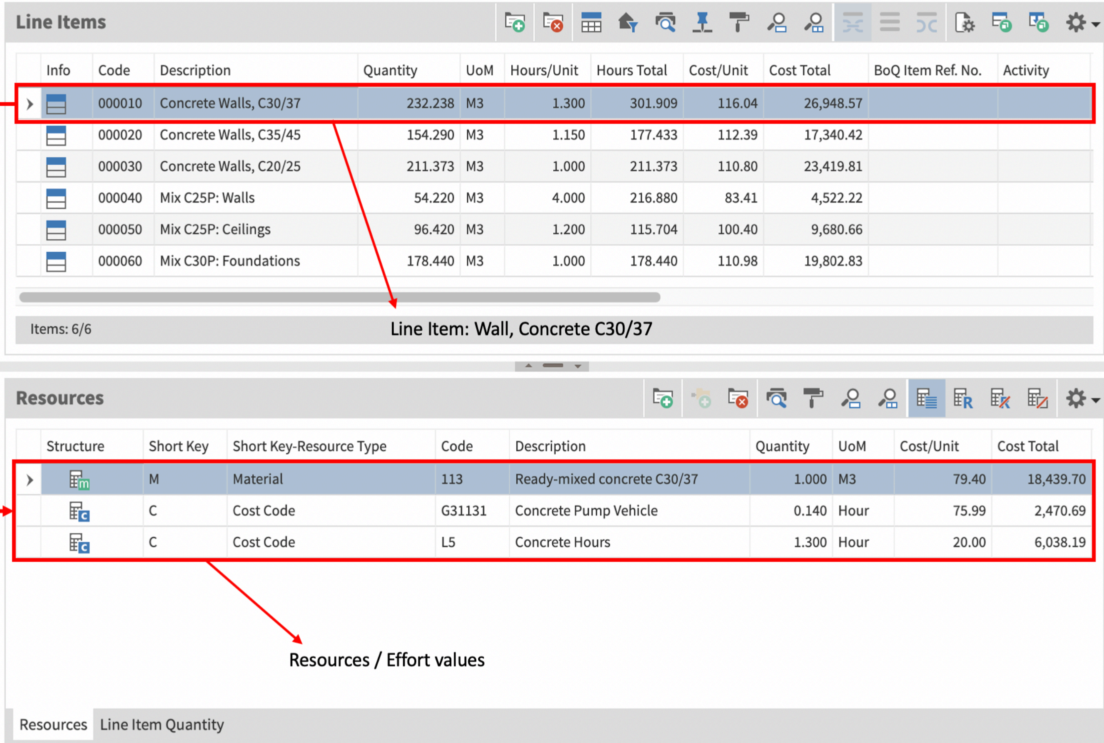


Figure 27: Line Items with corresponding resources

Depending on the procedure, the quantity values can be queried in the 3D model using a software-internal utility program via a predefined or individually developed Java script. The module "Construction Systems" of the iTWO 4.0 software platform is used for this purpose. This module allows a variety of filter variants to determine the model elements that are being searched for. The filters contain unique criteria, which are defined based on nested and / or / not / is equal (etc.) links. The following graphic shows an example of the filter presets of the "Construction Systems" module in iTWO 4.0 (Figure 28):

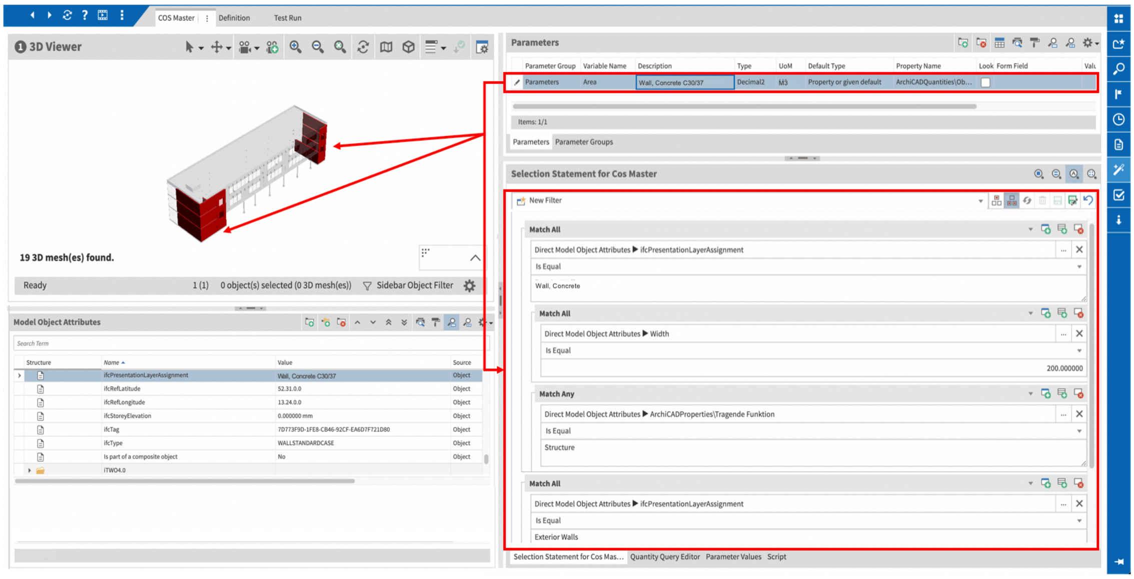


Figure 28: Determination of a model object by filters in iTWO 4.0 (Exterior wall; Width 200.0 mm; Structure) - *the BIM was provided by Technische Hochschule Mittelhessen; Germany*

In addition to the filter options, the "Construction System" module offers an environment in which individual Java-Script programs can be written and executed. With the help of these scripts, attribute values of the filtered model elements can be addressed and read out. In addition, Line Items can be automatically generated in the "Estimation" Module via Java script and the values (here: quantities) including their units can be entered into the corresponding fields of the Line Items (Figure 29).

An example of a Java script is shown by the following figure, which is used to retrieve the values of the attribute "Volume" of all model objects named "Concrete Walls" from a 3D BIM. Furthermore, the script generates a Line Item in the module "Estimate", where the term "Concrete Walls, C30/37" is entered into the field "Description". Next, the "volume" values are accumulated and transferred to the "Quantity Item" field of the Line Item. In addition, the field "UoM" (Unit of Measurements) receives the value "M3" for cubic meters.

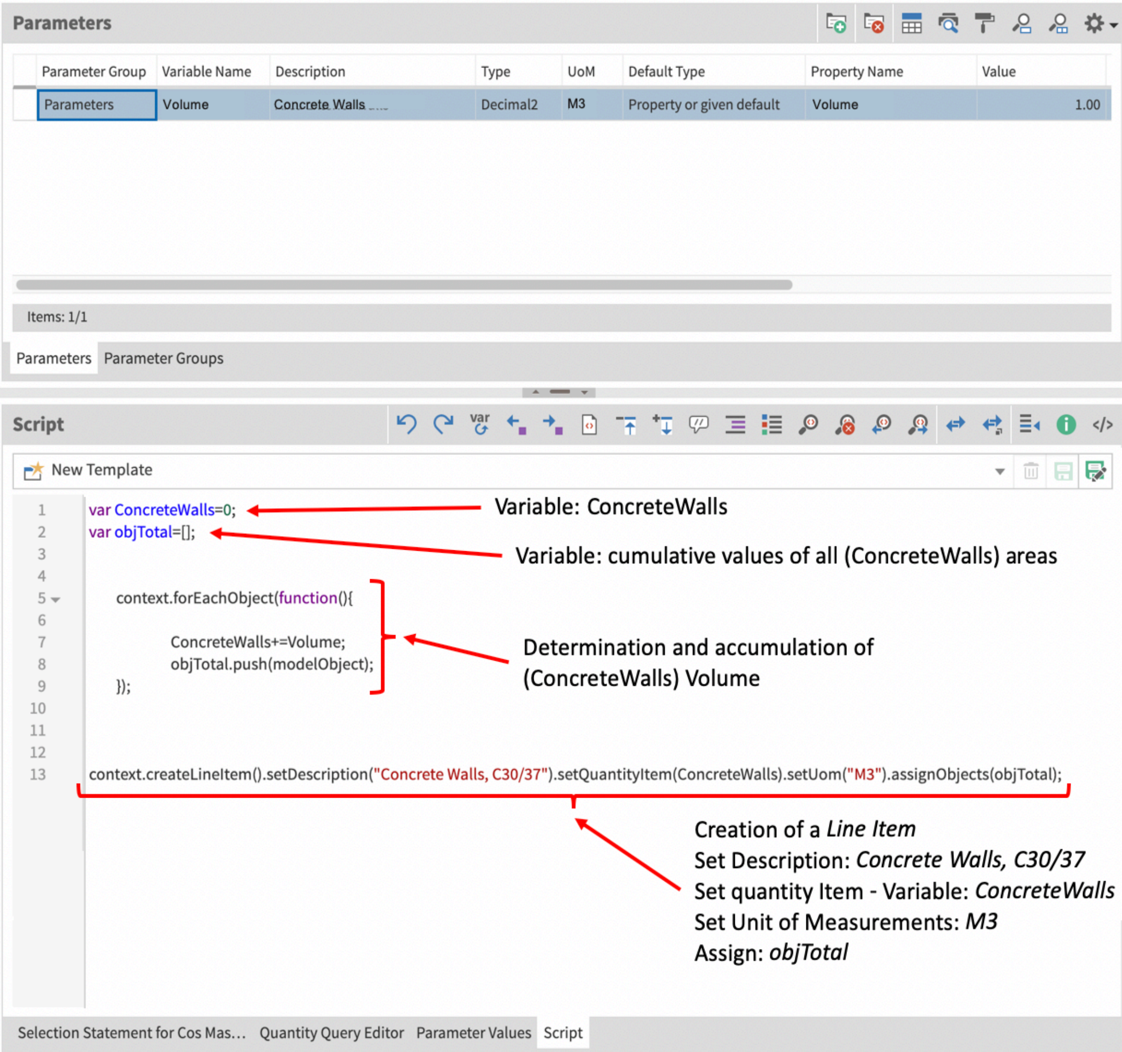
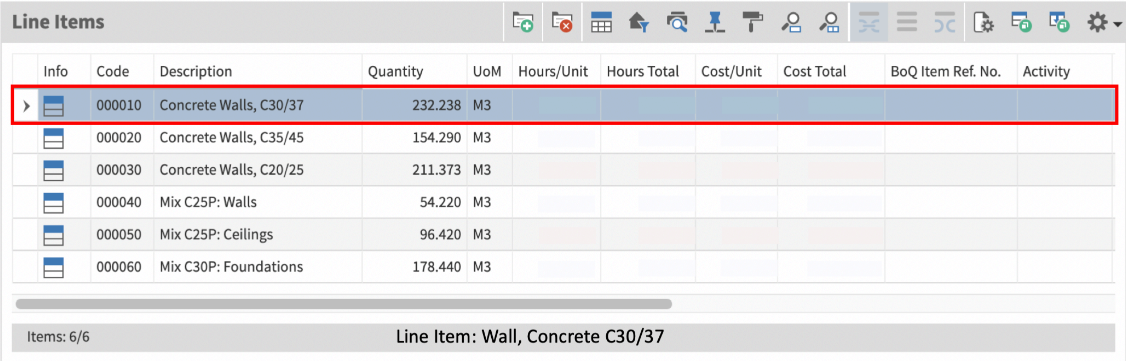


Figure 29: Example: Java Script-based quantity takeoff (QTO) and creation of a Line Item

The script can be executed in the "Estimation" module within iTWO 4.0. First the model is filtered according to the selected criteria. Only those model elements that have been found by the object filters are available for the attribute value query. For a better representation and assignment of the filtered model objects within the overall model context, all existing model objects can also be displayed additionally. For a distinction between "active and inactive elements", the inactive elements are greyed out (see Figure 28).

In the next step, as described above, the Line Item is created including the corresponding specifications and contents (see following figure). For this purpose, the corresponding attribute values of the model objects are retrieved, cumulated and provided with the assigned units of measurement.



Line Items

	Info	Code	Description	Quantity	UoM	Hours/Unit	Hours Total	Cost/Unit	Cost Total	BoQ Item Ref. No.	Activity
›		000010	Concrete Walls, C30/37	232.238	M3						
		000020	Concrete Walls, C35/45	154.290	M3						
		000030	Concrete Walls, C20/25	211.373	M3						
		000040	Mix C25P: Walls	54.220	M3						
		000050	Mix C25P: Ceilings	96.420	M3						
		000060	Mix C30P: Foundations	178.440	M3						

Items: 6/6 Line Item: Wall, Concrete C30/37

Figure 30: Example: Line Items created by Java Script

As illustrated by Figure 30 the example Line Item "000010 Concrete Walls, C30/37" was created. The cell "Quantity" shows the value "232.238" with the unit "M3". In this way, all required Line Items can be created automatically and filled with the corresponding contents. Once all Line Items have been created, the links to the effort values of the calculation can be established as described above. The calculation approaches are multiplied with regard to the construction time and cost values per unit by the total quantity values of the Line Items. This results in the total costs and cumulated production times, which is required for the planned construction work.

6.2.4. Technical Implementation of the 5D Approach

Based on this procedure, the model quantities are determined and the corresponding Line Items - including quantity values and corresponding UoM`s - are created. In a next step, based on the Line Items, the cost calculation and determination of the required construction times can be conducted. Of particular importance, when using the 5D-PROMPT method, however, is the linking of the Bill of Quantity (BoQ) positions and the schedule activities with the 3D BIM objects model by using the previously created Line Items. For this purpose, in the iTWO 4.0 module named "Bill of Quantities" the BoQ positions required for the tendering and awarding of construction services are created (Figure 31).

Structure	Reference No.	Outline Specification	Quantity	UoM
	SW.20.	Structural Work		
	20.	Concrete Work		
	20.10.	Exterior Walls - Ground Floor		
	20.10. 10.	Concrete Walls, C30/37	232.238	M3
	20.10. 20.	Concrete Walls, C35/45	154.290	M3
	20.10. 30.	Concrete Walls, C20/25	211.373	M3
	20.10. 40.	Mix C25P: Walls	54.220	M3
	20.10. 50.	Mix C25P: Ceilings	96.420	M3
	20.10. 60.	Mix C30P: Foundations	178.440	M3

Figure 31: Example: BoQ structure

With regard to the linkage of the schedule processes, it is important to note that the structure including quantity values of the Line Items, as well as the structure of the BoQ’s, are still completely arranged according to the trades and not yet according to the chronological sequence of the construction work. In order to link the schedule processes with the BoQ processes and the corresponding model objects, a project structure plan is developed (Figure 32), which is equivalent to the BoQ structure. In a later step, the project structure plan will be further developed into a construction sequence schedule. The data sets of the Line Items will be split accordingly and reassigned to the model objects as well as the activities of the construction schedule. Thus, the construction schedule becomes the leading structure, which sets the basis for further planning.

The creation of BoQ positions and schedule processes basically corresponds to the procedure of common tender as well as schedule software solutions. Here, pre-defined BoQ’s and schedules can also be imported via a software-internal interfaces or just implemented from already existing projects. The effort values on which the calculation and scheduling is based are used for these process steps as described above.

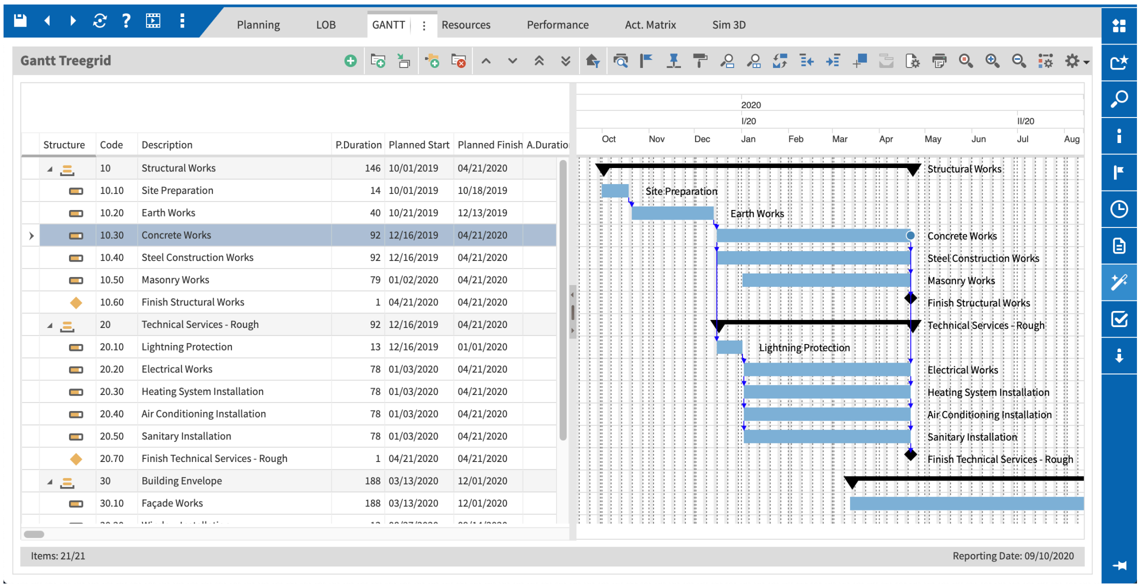


Figure 32: Example: Project structure plan as a Gantt tree grid

Once the Line Items have been created and linked to the model elements, the BoQ positions and the schedule activities can be assigned. For this purpose, the Line Items are linked to the corresponding BoQ items and schedule activities via drag & drop. The following two figures show examples for linking the model elements with the corresponding BoQ positions (Figure 33), as well as the schedule operations (Figure 34):

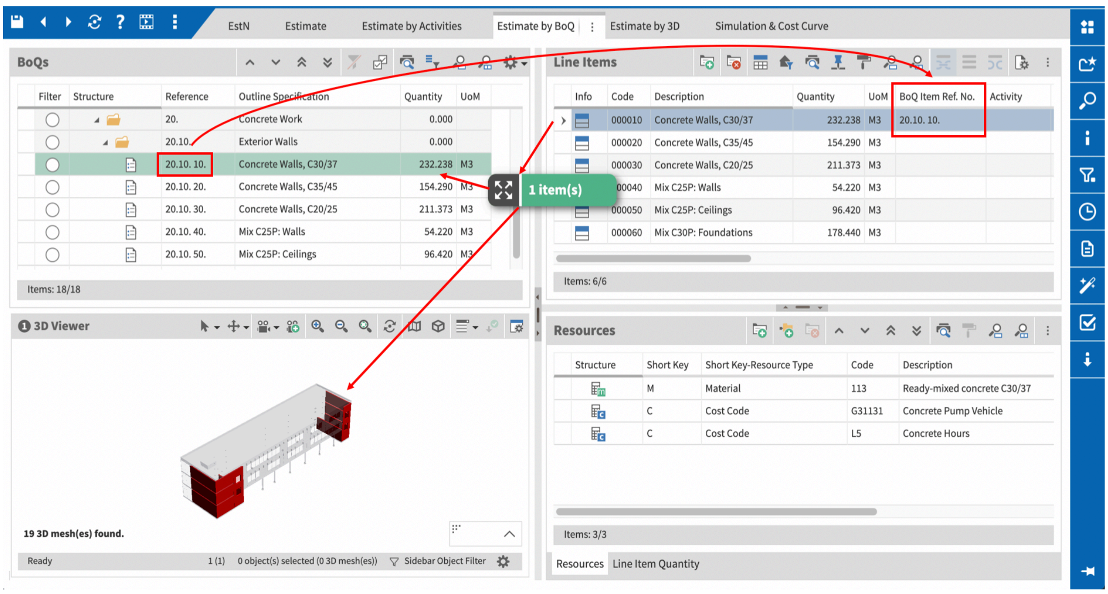


Figure 33: Interlinkage of Line Item, BoQ position, and model objects per drag&drop – Link is represented by the Line Item position

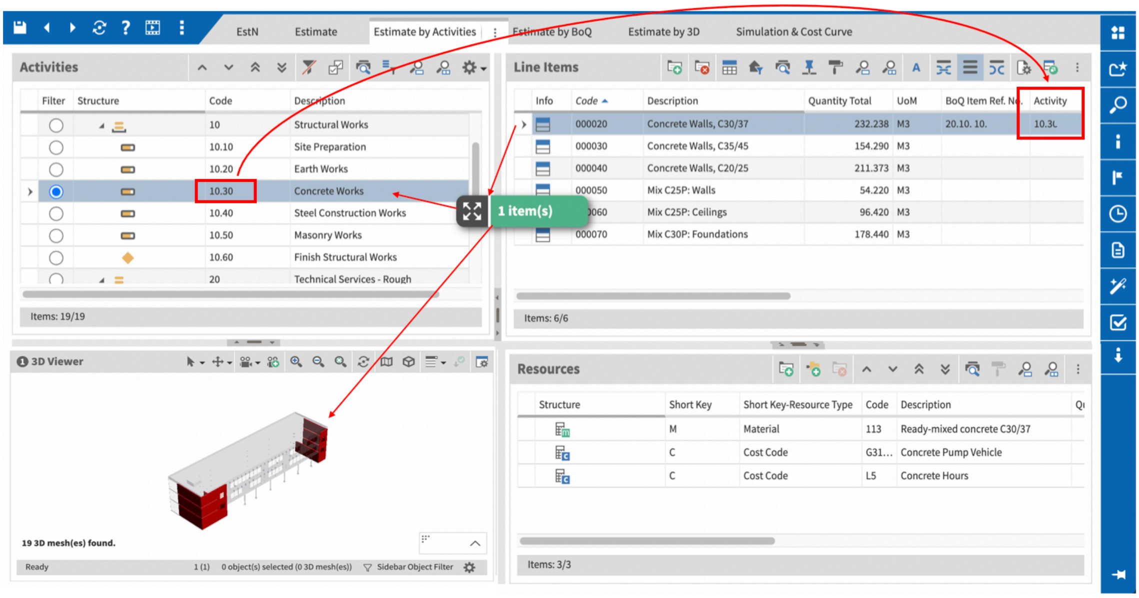


Figure 34: Interlinkage of Line Item, schedule activity, and model objects per drag&drop - Link is represented by the Line Item position

In a next step, the sequence numbers of the BoQ positions are entered in the field "BoQ Item Ref. No." of the Line Item. The activity numbers of the schedule activities are transferred to the "Activity" field of the Line Item. The fully functional process of creating a 5D building model represents the first main phase of the 5D-PROMPT method. The sequence of the process steps can be arranged so far according to the following example:

- Development of the 3D project model with regard to the BIM approach (BIM-capable CAD software [Revit, ArchiCAD, etc.]).
- Calculation of model object quantities by selecting quantity attribute values based on a Java script - or calculation of the quantities based on the geometric properties of the BIM model objects.
- Creation of Line Items as linking elements.
- Development of trade-specific BoQ’s.
- Determination of costs (calculation of costs according to cost groups/resources based on model quantities and the time-based effort values).
- Creation of schedule activities (project structure plan).
- Linkage of model objects with BoQ positions and schedule activities through Line Items; (see Figure 35).

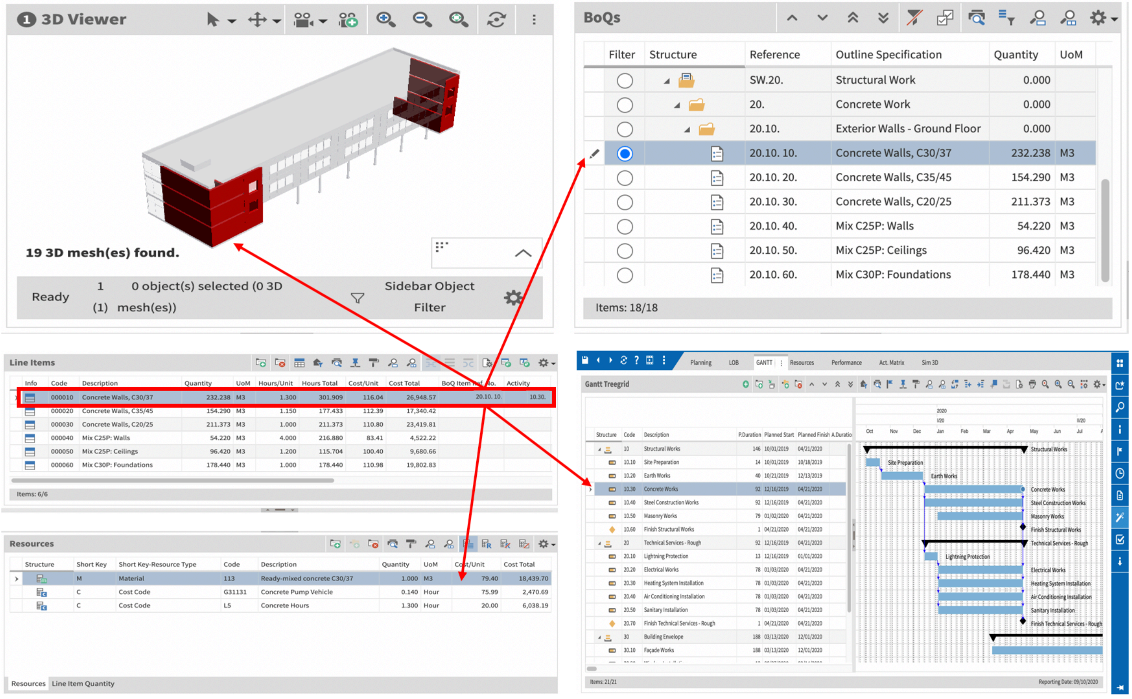


Figure 35: Technical representation of the 5D approach with iTWO 4.0

6.3. Tendering and Awarding of Subcontractor Services

Once the bill of quantity positions has been created and linked to the Line Items, the usual process of tendering and awarding of subcontractor services can take place. The process steps, which are required, are shown in the graphic below (Figure 36):

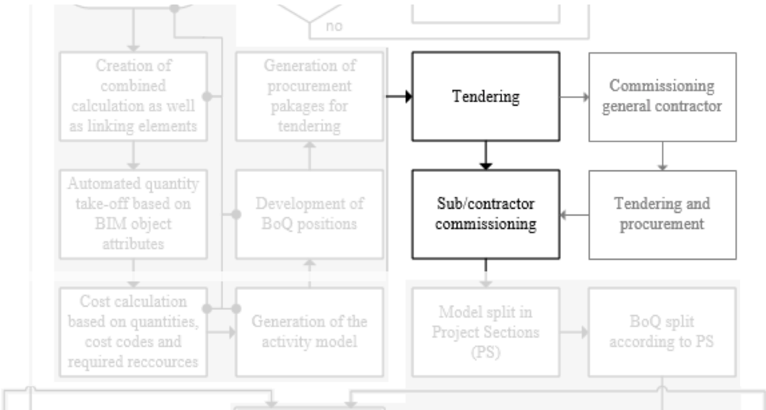


Figure 36: Process for tendering and procurement of general/subcontractor services

Here it is important to mention that the awarding of all trades must be completed before the execution of the construction work can begin. The reason is that the project team, which controls and monitors the multi-flexible execution organization of the construction work, is composed of the contractor's foremen, as well as the client's site- and project managers; this principle has already been successfully applied by the Last Planner System and is therefore also implemented in the 5D PROMPT method (Ballard 2000).

According to the scenario described above, the awarding of all subcontractor services requires a considerable amount of time, which also postpones the start of construction work by a certain period of time. At first glance, this shift appears to be a negative influence on the project`s duration caused by the implementation of the 5D PROMPT method; however, the postponement of the time axis should be used by project managers to check and optimize the current state of planning for technical feasibility. Furthermore, the construction process should be structured and prepared according to the process described in the following chapter. Moreover, due to the agile execution organization a shortening of the overall project duration is expected.

The tendering, awarding and contracting process can be performed using the fully integrated tendering, awarding and contracting modules of the iTWO 4.0 software platform. This is recommended for the reason to avoid possible loss of information due to necessary interfaces to other software tools. In addition, duplication of work steps can be prevented, and the creation of incorrect data records can be excluded. In general, the process of tendering, awarding and contracting can continue to follow the previously known and commonly used working methods. Particular importance is placed on the creation of legal documentation for subcontractors, where information on multi-flexible, organized procedures of construction services and the necessary commitment to the execution terms are defined as a significant contractual obligation. As such, an agreement between the client and contractor is effective if both parties consent to the appropriate contractual conditions.

6.4. Implementation of Important Project Events

In the next step, the previously developed project structure plan is further developed into a construction sequence schedule. It is based on the project-related and execution-oriented construction sequence of all trades and required services. These are put into an appropriate chronological - waterfall-based - order (Figure 37); the execution times are based on the duration of the previously determined production times, based on the applied effort values.

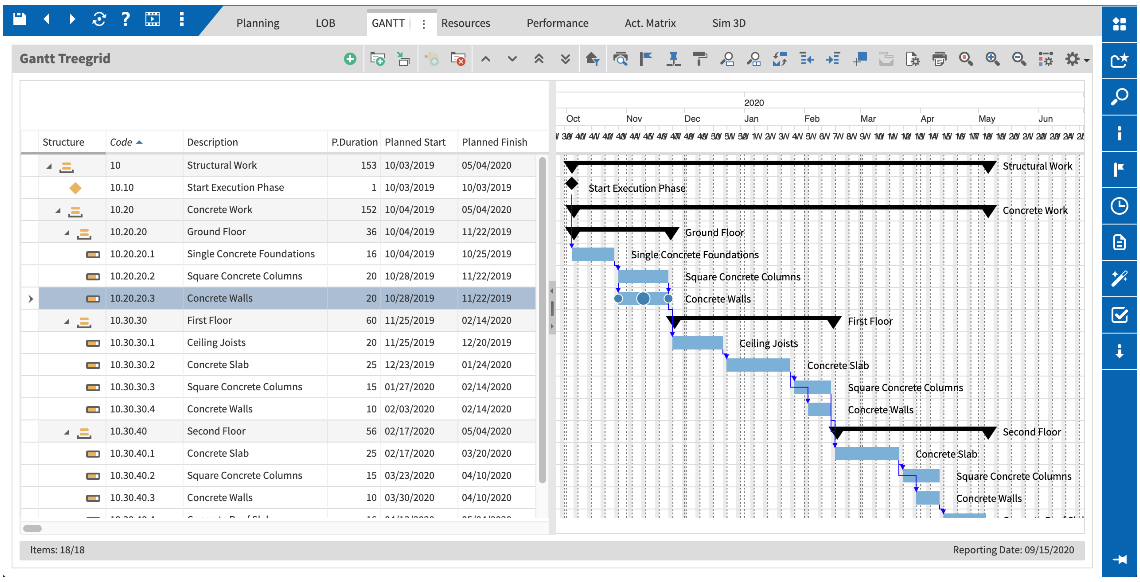


Figure 37: Development of the waterfall-based construction schedule with chronological structuring of the construction sequence

The development of the construction schedule is used for the subsequent execution of the construction process simulation (see process chart, Figure 38). This is required because of two essential process steps. On the one hand the construction process is examined in this way with regard to optimization possibilities, like the determination of date collisions and unused temporal resources; on the other hand, important project milestones (project events) within the construction process can be specified and determined.

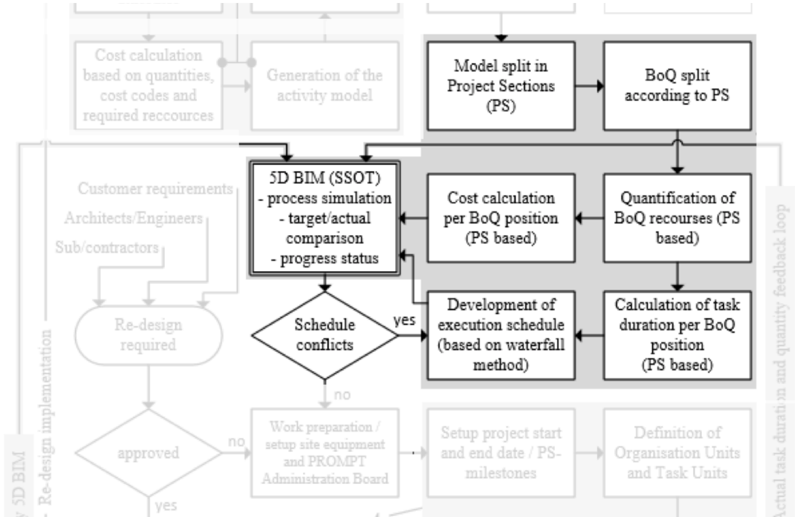


Figure 38: Process of model split and allocation of corresponding schedule activities and cost positions for the determination of project start/end date and important project milestones

Important project events are the start and end of construction as well as time-related milestones, which represent the completion dates of previously defined project sections. Thus, for an optimally structured and improved agile construction process organization, it is of essential importance that time-based indicators (milestone dates), which characterize essential project phases and intermediate deadlines, are determined and implemented during the construction planning phase. For this purpose, it is necessary to divide the 5D BIM into individual construction phases (Project Sections - PS). The PS are customizable in type and size, but should, if possible, include comprehensive project sections, such as individual building sections or floor levels.

For the determination of the project specific milestones, it is required to cluster the corresponding model elements, BoQ positions and allocated schedule activities of the concerned project sections. Therefore, it is required to split each Line Item into the number of created project sections. The quantities are apportioned between the Line Items according to the associated model elements. The following graphic (Figure 39) shows the associated software-based procedure. Also, an example of a combined project section is shown in the bottom right-hand section of the following figure. The associated model elements are shown in red. The separator-element, which divides the project sections is marked by a yellow vertical area.

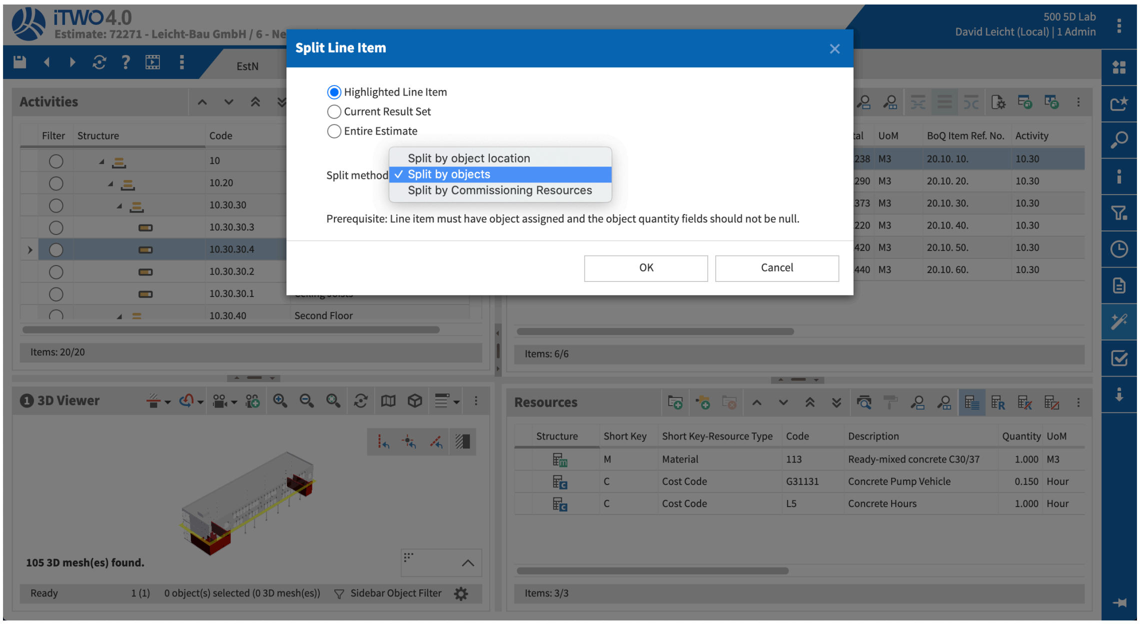


Figure 39: Split of Line Items

In the following step, the Line Items and model elements are linked with the activities of the previously developed construction sequence schedule. The figure below (Figure 37) illustrates the linking process. Through the linkage, the cells titled “Activity” receive a new process number, which is derived from the "code" field of the related schedule activity.

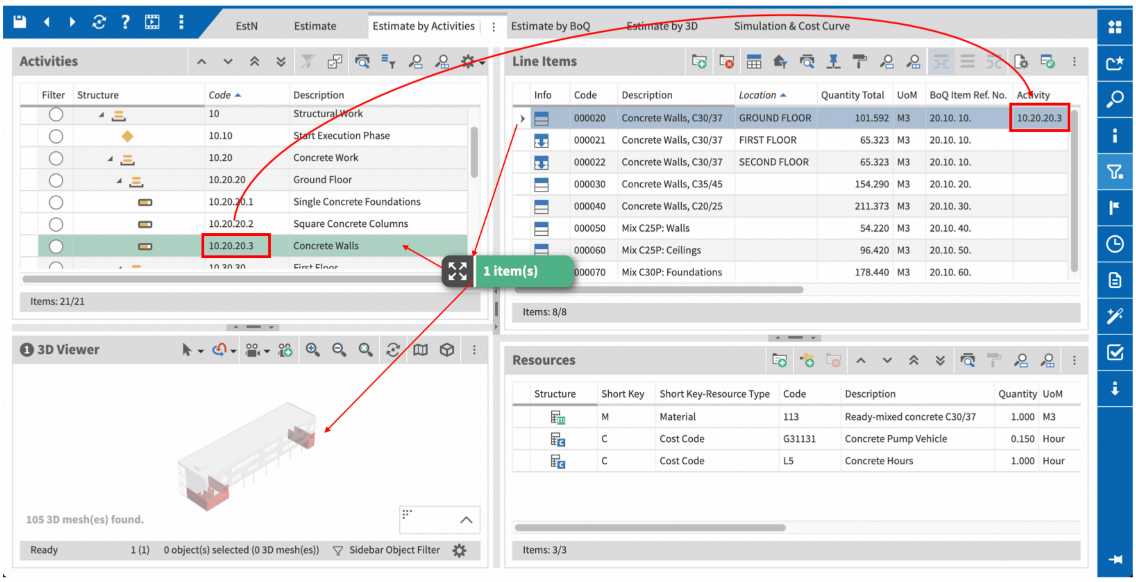


Figure 40: Linking process of the split Line Items with the associated model elements and corresponding schedule activities in accordance with the predefined project sections (PSs)

Once the Line Items and the model elements are assigned to the operations of the construction schedule, the simulation of the construction process can be performed in accordance with the construction stages. The milestones, which refer to the completion of the relevant construction phase, can be inserted into the construction schedule. The following graphic (Figure 41) illustrates the software-based simulation of the construction process, however, without the project milestones yet. The current situation shows the trade-related completion of the first floor (model elements highlighted in grey) and the building parts which are currently in the execution process (highlighted in red).

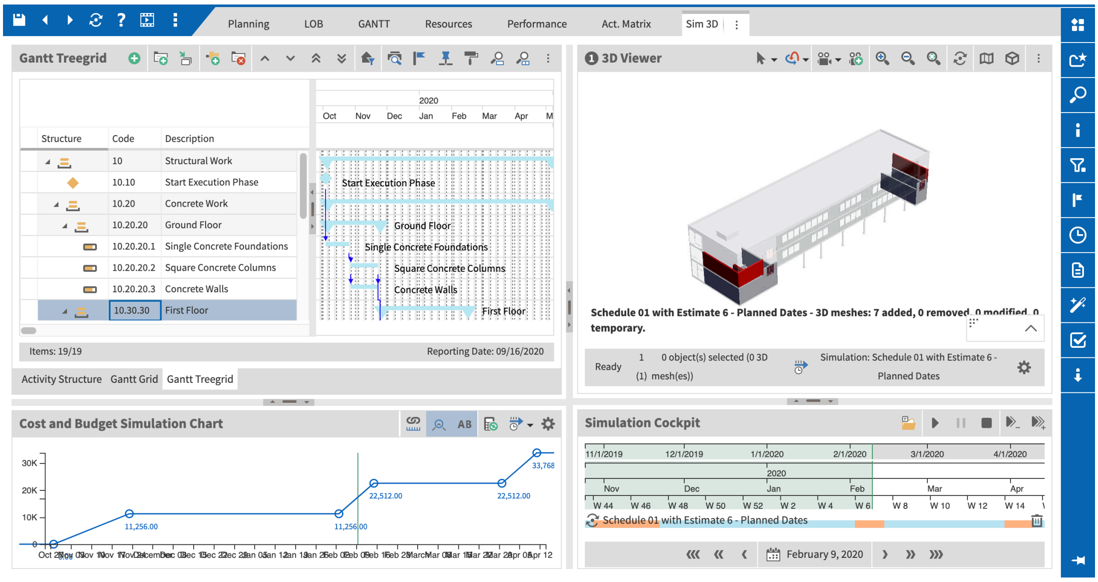


Figure 41: Exemplary representation of the construction process simulation

Now, the project milestones required for the multi-flexible construction process organization can be integrated into the construction schedule. For this purpose, milestone activities are inserted at the particular points in the schedule where the completed construction phases were determined by the preliminary simulation - as shown in Figure 42:

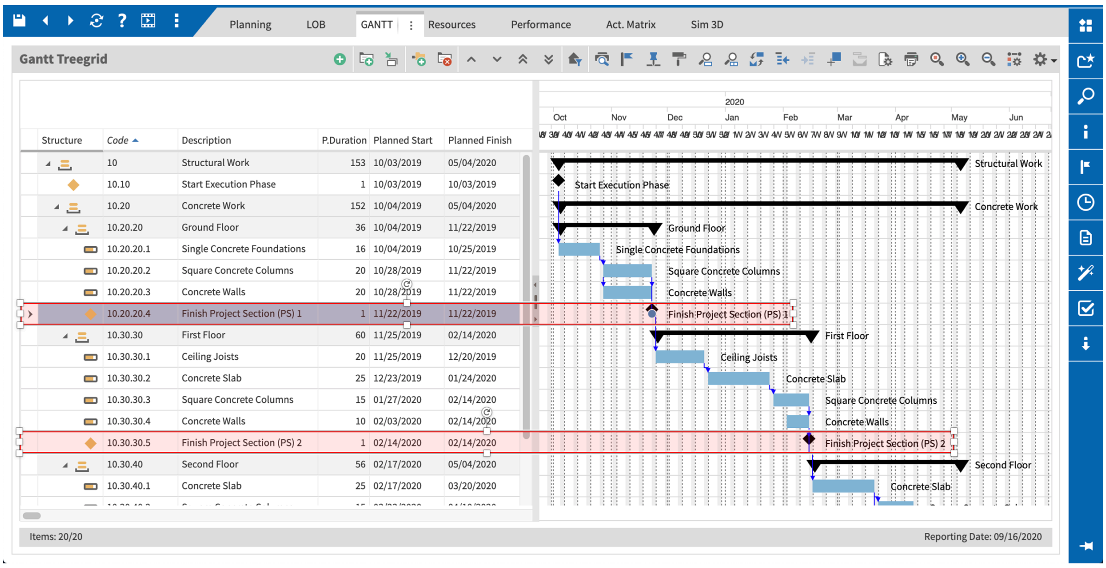


Figure 42: Allocation of relevant project milestones to the construction schedule

Once the milestones have been integrated into the construction schedule, a subsequent simulation of the planned construction process can take place. The process for this theoretical simulation is shown by Figure 43:

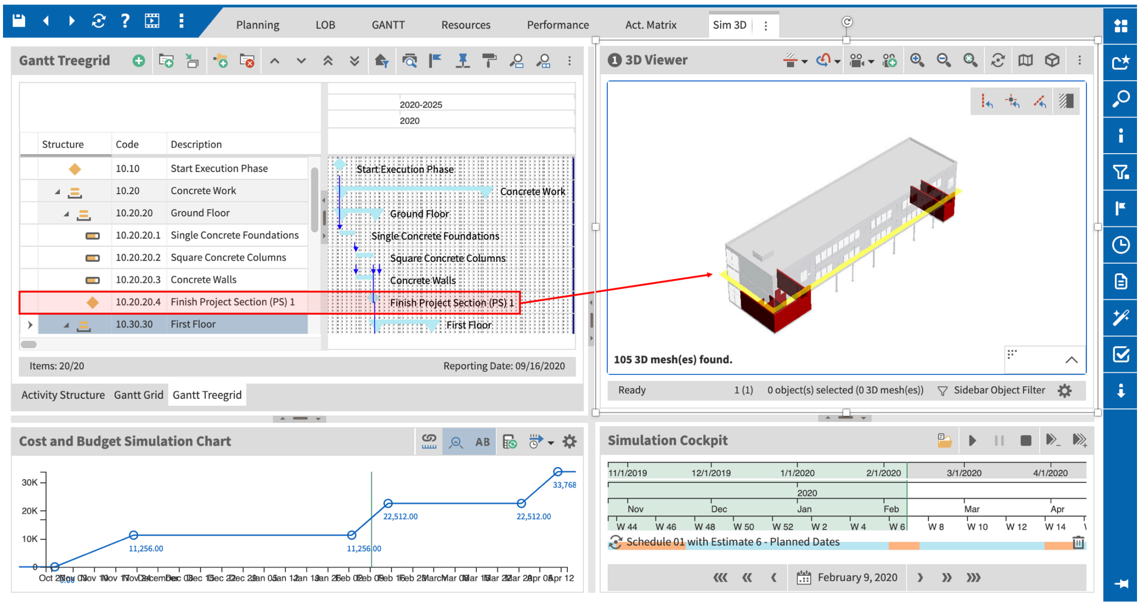


Figure 43: Construction process simulation according to predefined construction stages

6.5. Transfer of the Project Milestones into the Construction Phase

To form the conditions for an aspired agile organization of construction execution, a basic grid should determine the direction of the work execution proceedings. For this purpose, the 5D BIM was previously split horizontally and vertically into approximately equal-sized PSs. The corresponding BoQ positions and schedule activities were divided and re-compiled accordingly. After schedule reorganization, the project start/end date (project frame [PF]) and the start/end dates of each PS have been determined.

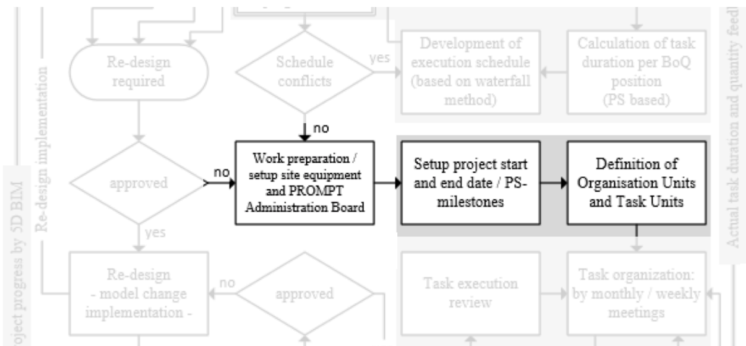


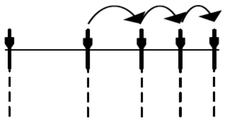
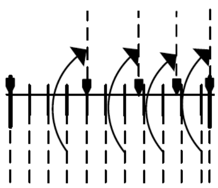
Figure 44: Transfer of project start/end date as well as project milestones and setup of the PROMPT administration board

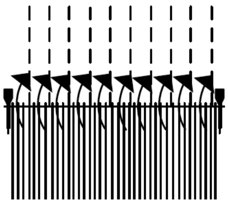
In order to keep the multi-flexible organized construction execution process as flexible as possible, only the events of the PF and PSs should be transferred to the project execution phase (Figure 44). Any other information provided by the waterfall-based schedule possesses no further use for the remaining course of the project. However, applied effort values within the project planning phase are updated or corrected with regard to determined deviations between planned (as-planned) and actual used (as-built) resource values.

6.6. Multi-flexible Project Execution Organization

A core aspect of agile organized work execution concerns the collaborative competence of the contractors (capacity for teamwork) involved in the execution process. All construction trades should be tendered and contracted/subcontracted at this point in the project; furthermore, specific project organization requirements must become an integral part of the contractor/subcontractor agreements. To manage/organize project execution onsite, an agile execution organization board (hereafter referred to as the PROMPT Administration Board) is formed in close cooperation between the foremen and site/project manager. The basic approach in this method resembles the LPS/Scrum/Kanban project organization boards; however, the present method differs in its setup and arrangement (Ballard and Howell 2003, Streule, Miserini et al. 2016). The PFs and PSs define the general project guidelines and determine significant milestones required to set the deadlines for the individual PS delivery as well as delivery of the entire project. Thereafter, fixed time periods are established to manage and review on-site execution, which is structured in accordance with a monthly and weekly sequence. Both, Organization Unit (OU) and Billing Unit (BU) are implemented in a monthly sequence (a deeper description of the meaning and purpose is given in the table below). In a weekly sequence the Task Units (TU) and Report Units (RU) are established. The form and concept of the PROMPT Administration Board are explained in Table 2:

Table 2: Leading structure for development of the PROMPT Administration Board

Board Structure	Key Units	Project Management Compendium
Implementation of Project Start and End Date (PF)		
Project Start and End Date 	Project Frame (PF);	PROMPT Administration Board setup; Set project start-date/end-date for total project duration (derived from waterfall-based project schedule); Aim Project Sections (PSs)
	Organization: administration kick-off meeting	
Implementation of Project Sections (PSs)		
Project Sections 	Project Sections (PSs);	Set Project Section milestones: start-date/end-date (derived from waterfall-based project schedule); Superior task summary; Agile reconciliation of task order per PS (end-to-front organization); Feasibility evaluation—compliance with PF; Commitment to agreements
	Organization: Administration kick-off meeting	
Implementation of Organization Units (OUs) and Billing Periods		
Organizational Units (monthly review of PS compliance)	Organizational Units (OUs)	Set Organization Unit start-date/end-date (duration: 1 month—determination of fixed weekdays is compulsory due to synchronization with weekly Task Unit sequence: 1 month ≈ 4.4 weeks; Set start date: e.g., every last Friday of each month; Set end date/due date for monthly meeting: e.g., every last Thursday of each month; Agile reconciliation of target order per OU (end-to-front organization); Definition of execution scope per Task Unit (TUs are based on model sections: rooms; slabs; objects, etc.); Advanced organization of complex/risky tasks; Feasibility evaluation—compliance with Project Section milestones; Commitment to agreements (post-its)/review of finished Task Units/evaluation of target agreements
	(subordinated organization of project execution tasks);	
	Organization: monthly meeting	
	Billing Periods (period of partial invoicing)	Set Billing Period start-date/due-date: equivalent to OU dates; Invoicing according to finished, reported and approved Task Units

Implementation of Task Units (TUs) and Report Periods		
Task Units (monthly review of OU compliance)	Task Units (TUs)	Administration task definition—Set Task Unit start-date/end-date (duration: 1 week—determination of fixed weekdays is compulsory due to synchronization with monthly meeting of Organization Unit—in this example: every last Thursday of each month); Set start date: e.g., every Friday of each week; Set end date/due date for weekly meeting: e.g., every Thursday of each week; Agile reconciliation of targets per TU (post-its); Specific organization of complex/risky tasks; Feasibility evaluation—compliance with Organization Unit sequence; Commitment to agreements/review of finished model sections/evaluation of delays and target agreements
	=∑ pre-defined model sections (rooms/walls/slabs, etc.) that could be finished within one week by a trade-specific execution team;	
	Organization: weekly meeting	
	Report Periods (weekly project execution performance report)	Set Billing Period start-date/due-date: equivalent to TU dates; Reports according to finished and approved Task Units—Task Unit finished (100%); Task Unit in progress (50%); Task Unit open (0%)

The task organization graduates from general to particular. Appropriate descriptions are provided in accordance with the specific levels of organization. The setup and formatting of the organizational structure (PROMPT Administration Board) is performed during an administration kick-off meeting conducted by the execution team members (foreman/project manager – contractor side; site/project manager – client side). The workflow and superstructure are outlined in Figure 45 and Figure 46. Since the project`s start/end dates and milestones for PS delivery are attached to the administration board, the OUs and TUs can be defined.

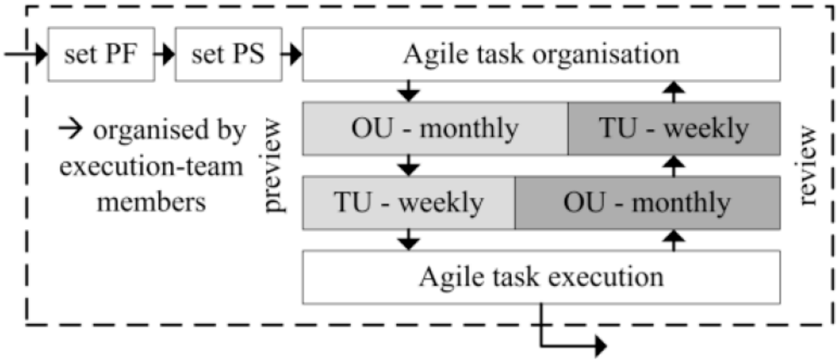


Figure 45: Process chart: Setup of the PROMPT Administration Board

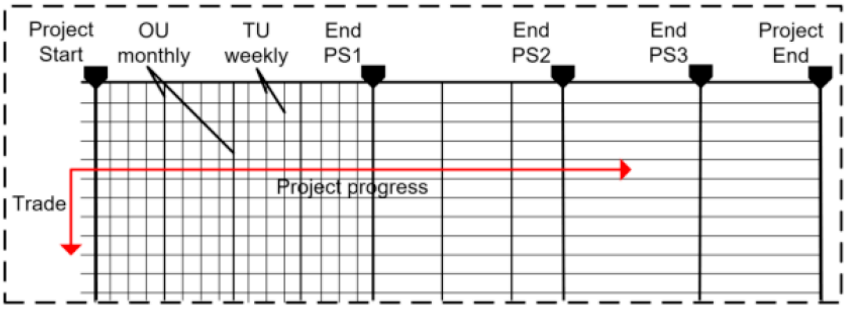


Figure 46: Setup and superstructure of the PROMPT Administration Board

Participation in monthly or weekly meetings is compulsory for each of the execution team members. Individual as well as general agreements determined during these meetings must be accomplished within the envisaged time frame.

6.7. Agile Work Execution

Once the structural procedure for executing the project has been defined using the PROMPT Administration Board, the construction work can begin. The process is illustrated by Figure 47:

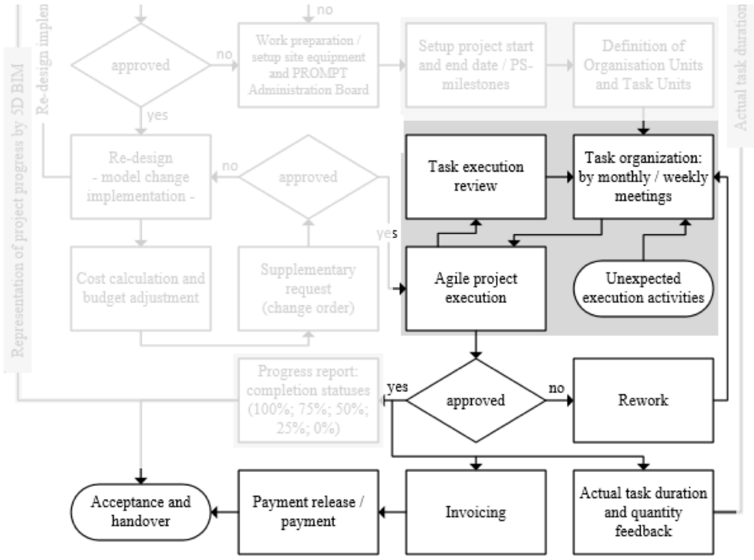


Figure 47: Process of multi-flexible work execution

Due to the agile work method, the construction process is organized and executed in a highly flexible manner. This enables rapid and precise reaction to unexpected events and ad-hoc change requirements. Additionally, necessary reworks or corrections of faults in the construction processes can be clarified and solved within the weekly conducted review meetings in order to prevent disruptions and delays of remaining construction works. With the frequent documentation of the construction work, the execution organization team is continually updated regarding the status of the construction work.

6.8. Implementation of the Information Feedback Loop

The construction progress is evaluated and updated during the weekly meetings (RP`s) based on the actual completion status values of the planned (trade-specific) targets. The completion status values equal 100% for completed, 50% for partly completed, and 0% for pending activities. The actual status values are displayed in colored markups (green, yellow, and grey, respectively) by the 5D BIM, which is employed as an SSOT, as illustrated by Figure 48 below:

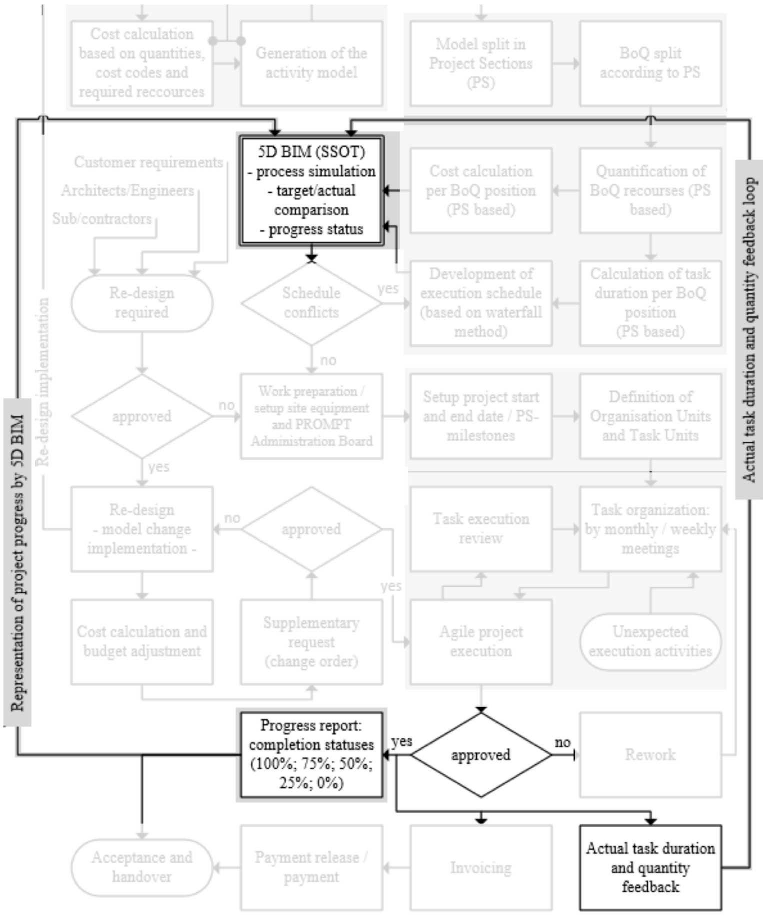


Figure 48: Process of the information feedback loop and 5D BIM as the single source of truth (SSOT)

Invoices can be issued in accordance with the BP`s (monthly). The basis for payment approval concerns the actual (trade-specific) competition status of the accumulated monthly activity performance. To achieve sustainable improvement of the planning accuracy, substantial deviations between the planned and actual execution durations are identified and evaluated by the execution team members and reported back to the project planning department to implement a sustainable correction process for time-based calculation matters. Furthermore, deviations between planned and applied resources can be immediately determined. In this way, the planning accuracy for future projects can be substantially improved.

7. Comparative Case Study

An initial implementation and performance test of the 5D-PROMPT method was conducted using two real practice construction projects as a comparative case study. To pre-classify the workability and expected benefits of the new approach and to make it comparable to the currently common method, one construction project was conducted according to conventional planning and execution methods, as described in the process chart in Figure 19 (hereafter referred to as Project A). The project was located in Ludwigsburg, a city in Southern Germany. During the same time period, an equivalent construction project was conducted according to the 5D-PROMPT method, as described in Figure 21 (hereafter referred to as Project B). This was also located in Ludwigsburg. Project A and B were conducted by the general contractor company Heinrich Schmid Systemhaus GmbH and Co. KG during the years 2018/19 (Location: Southern Germany; City: Ludwigsburg; Building types: Office building). A total of 21 trades were planned and executed by the project stakeholders over a period of nine months for Project A and 11 months for Project B. With the exception of the structural works and parts of the technical building equipment, all trades were organized by Heinrich Schmid Systemhaus GmbH and Co KG.

In this study, it is assumed that the process sequence and implementation of Project A is generally known. Nevertheless, the process chart of the project’s process is presented in Figure 19. Due to the development and initial implementation of the new method, the following section describes the procedure for conducting Project B. To enable better understanding of the differences and key characteristics of the two methods, the basic process steps of both projects are compared in Table 3.

At this point, it must be stated that the architectural planning as well as the QTO of both projects was also based on 2D CAD techniques besides the 3D BIM-based planning and QTO, as these represented realistic projects. This was unavoidable, as errors or failure in the implementation test posed a high risk for both the project and the participating companies. This dual-track procedure ensured that, in the event of unsuccessful completion, both projects could be completed in accordance with the conventional methodology.

Table 3: Overall process steps of Project A compared to Project B

Project Phase+D9:F22	Process Steps-Project A	Process Steps-Project B
Design	2D/3D CAD design 2D/3D-based quantity take-off * BoQ development and cost calculation * Determination of execution activity effort values * Rough estimation of execution durations	3D BIM design 3D BIM-based quantity take-off 3D BIM-based BoQ development linked to model objects 3D BIM-based schedule development linked to model objects 5D Building Information Model split (project sections) 5D BIM-based construction process simulation/optimization
Tendering/Contracting	Software-based tendering and contracting	Intergarted, software-based tendering and contracting
Execution	Construction execution schedule development (waterfall-based) * Construction work execution based on Gantt-chart Work organization and controlling by individual site manager	Agile work organization and controlling - team-based Agile work execution and management 3D model-based execution status representations As-built information feedback loops

* without model linking.

As previously described, the design of Project B was partly based on a 3D BIM. This model was provided by Contelos GmbH, a virtual-modeling company. The construction software developer RIB Software SE provided the software tool iTWO Baseline, which was employed to create the required interconnections between the individual model objects, the corresponding BoQ positions, and scheduling activities.

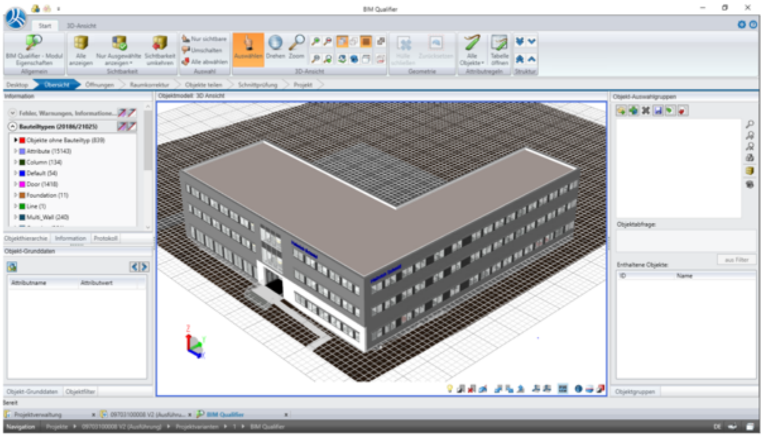
Furthermore, the model split operations, construction process simulation/optimization, tendering and contracting of subcontractor services, and 3D model-based execution status representations were conducted or developed by this software. To minimize the risk of method failure, in addition to the 3D BIM, conventional 2D CAD project plans were also created and kept available for execution.

Since the 5D-PROMPT method was introduced to project stakeholders, continuous team coaching and individual training were required to acclimate the participating members to run the project. To ensure a solid foundation, all project-related contracts had to comply with the multi-flexible project’s execution requirements. The modeling company was further required to elaborate the 3D BIM to confirm the modeling guidelines of the applied 3D modeling software (Revit) and to make use of a harmonized project-wide BIM attribution. A substantial measure consisted of awarding and contracting all execution trades, which had to be completed before work execution began. Next, the execution organization team was formed, consisting of foremen, crew leaders, site managers, and the project leader. This team performed the setup of the PROMPT Administration Board using the time-regulated “project start and end date as well as milestone dates”, which was determined via the waterfall-based construction execution simulation. Moreover, monthly or weekly time periods for the OUs and TUs were added to the board to establish a static structure for the work execution organization.

After work execution started, the team determined, confirmed, and evaluated both upcoming and finished work execution tasks during monthly or weekly meetings. Daily work performance monitoring ensured proper target/actual provisions and provided information concerning the required execution durations. Actual building statuses were represented by highlighted objects in the 3D BIM. Deviations between the planned and required time and cost values were evaluated and gathered in a database to make future project planning more precisely predictable and reliable. The core process of the case study is represented and described in Table 4:

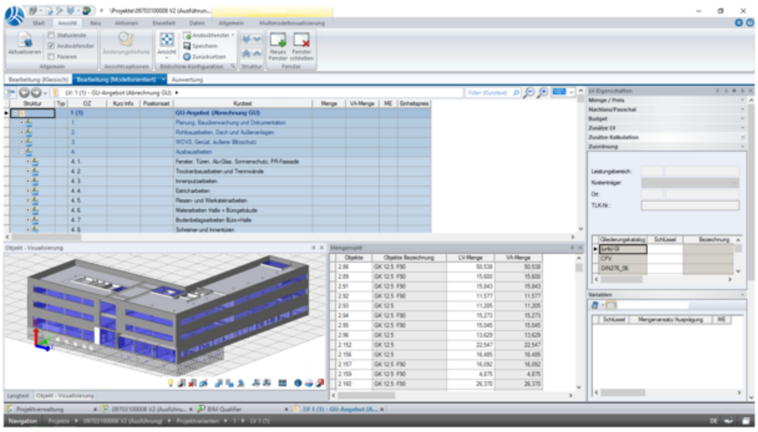
Table 4: Integrated software application and practical 5D-PROMPT workflow implementation

<u>(I) - 3D BIM design and model check</u>



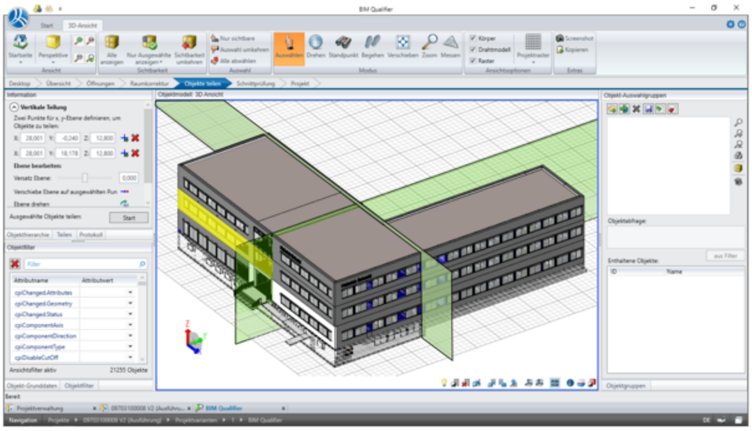
After the 3D BIM was designed using the 3D-BIM-capable software Revit, the model was uploaded to iTWO Baseline and checked for errors and comprehensiveness using the integrated BIM qualifier tool. This picture illustrates the 3D BIM.

<u>(II) - Interlinkage between BoQ positions and model objects</u>



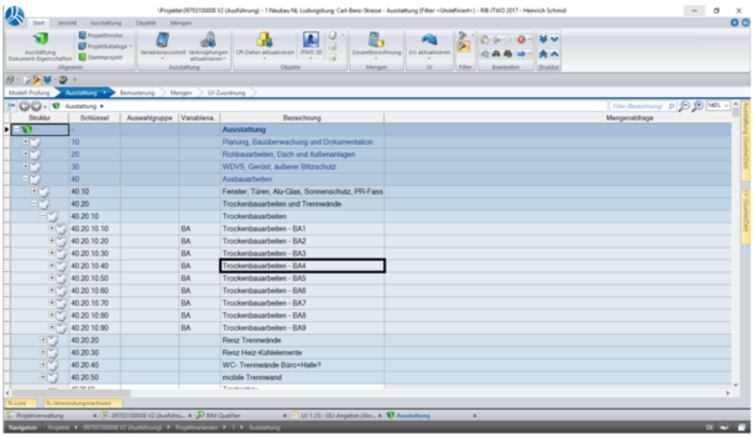
The second step involved developing the individual BoQ’s, including model-based quantity takeoff (QTO) and cost calculation based on resource-specific effort values. The BoQ positions were closely interlinked to the individual model objects.

(III) - 3D model split



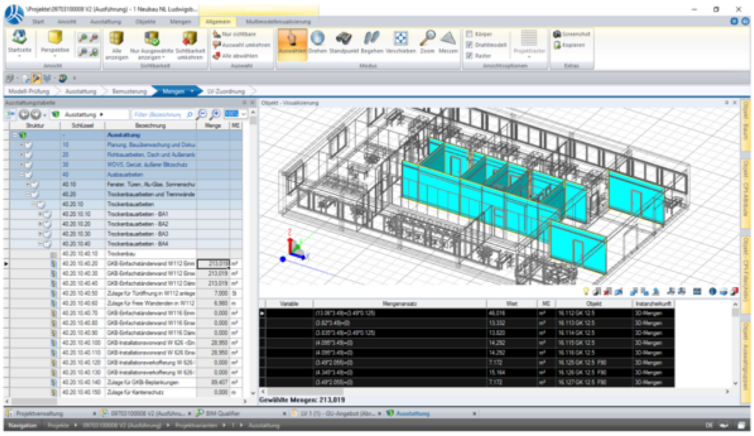
In order to pre-define the course for the agile organized construction work execution, the model was split into approximately equal-sized project sections (PSs). This was accomplished via the "Split Model" option.

(IV) - BoQ split



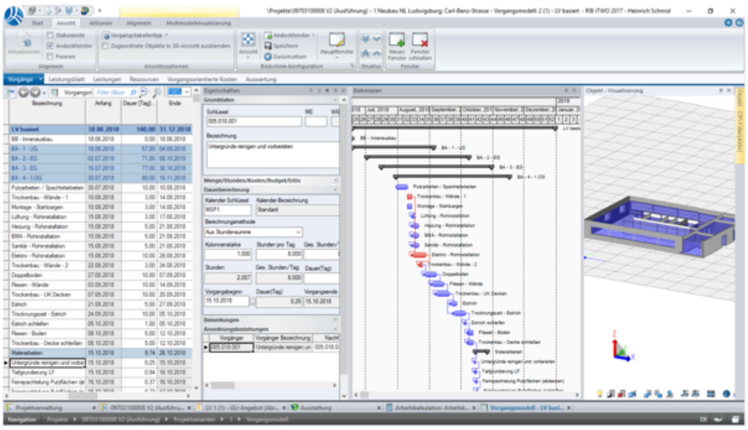
The individual BoQ's were split in accordance with the number of PSs; the BoQ structure remains unchanged; quantities were distributed in the next step; → 9 PSs ≙ 9 BoQ sections

(V) - Quantity distribution



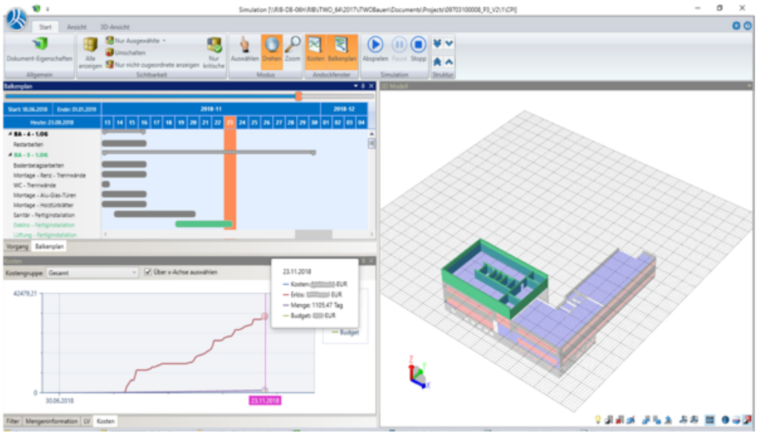
The model object quantities as well as the assigned BoQ positions (including resource effort values, corresponding costs, and execution durations) were divided and distributed based on the related PSs.

(VI) - Development of the waterfall-based construction schedule



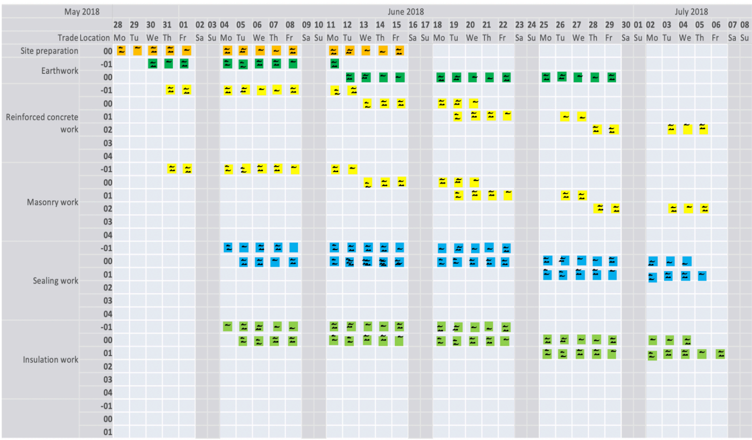
Next, the construction activities and associated execution durations were consecutively and chronologically listed in a waterfall-based project schedule chart. In the following step, the individual schedule activities were linked to the corresponding model objects and BoQ positions.

(VII) - Virtual project simulation and process optimization



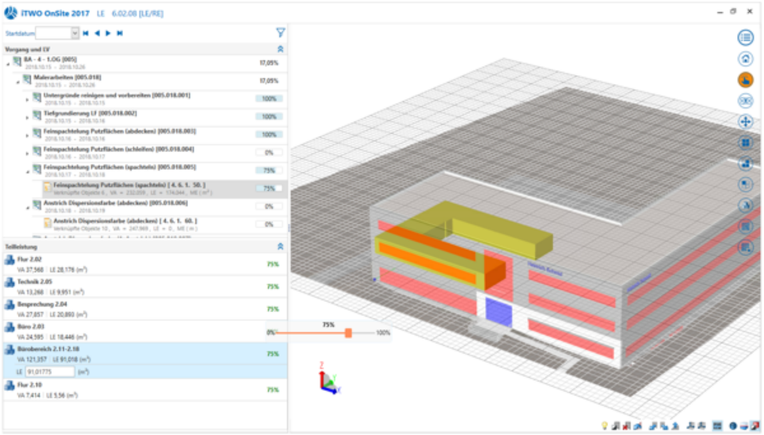
The project execution process was simulated, tested regarding collisions / bottlenecks, and optimized accordingly. Moreover, project start and end dates as well as milestones for PS delivery were determined.

(VIII) - Agile project planning*



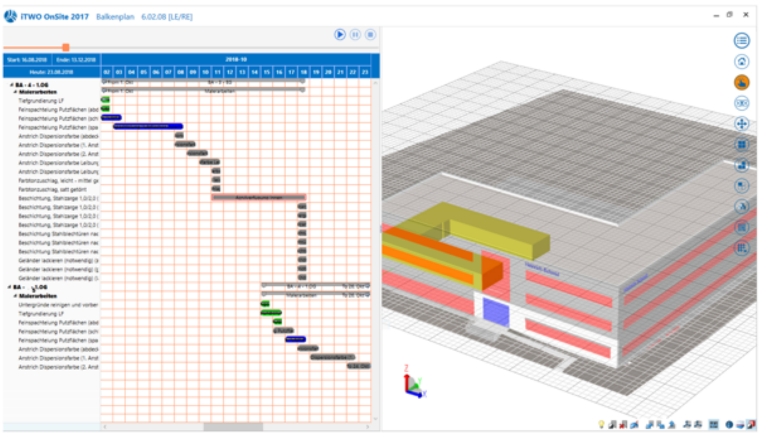
Setup of PROMPT Administration Board: Transfer of PF and PS milestones from the waterfall-based project schedule chart. Implementation of OUs and TUs. Team-based agile work organization and review (→ in accordance with Table 2) *schematic illustration due to German project language

(IX) - Work in progress measurements



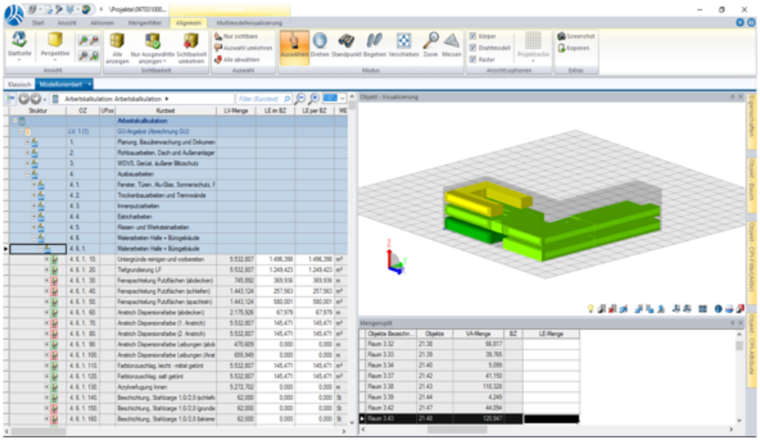
Next, accompanying the agile organized project execution, the TU completion statuses (100%; 50%; 0%) were continuously captured on site, accomplished using the integrated iTwo OnSite® software application. On this basis, trade-specific invoices were generated in accordance with the OUs / billing periods.

(X) - As-planned/as-built comparison and feedback loop implementation



From the OnSite® progress assessment, actual used quantities / resources and costs were determined. These values were then compared against the planned values. Deviations were reported back to the project planning department to be used for quantity / resource effort value updates; in this way, continuous improvement ensured static increases to future planning accuracy.

(XI) – Work-in-progress representation



The 5D-PROMPT workflow culminated in the project performance status representation, continuously presented by the 5D BIM. The model objects were highlighted in different colors according to the progress status (e.g., 0% grey, 50% yellow, and 100% green).

The performance values of both methods were determined using special Key Performance Indicators (KPIs - listed in Table 5) measured during/after the execution phases of both projects and subsequently evaluated by a multi-criteria analysis. The required KPIs were selected based on the findings of the literature study and an analysis of the current state project management approaches. As a comparison of the two construction projects would have led to inaccuracies due to a lack of absolute equivalence, a reference value was introduced as a benchmark for data collection. This value was set to 1000 m2 GFA (Gross Floor Area) and all measured values refer to th is parameter. Due to the practice-relevant character of the two accomplished projects, the specific project information, as well as all measured values, were precisely used within the calculations; however, due to the internal guidelines of the company Heinrich Schmidt GmbH & Co. KG they were only represented in this study by percentage or approximate values. The Key Performance Indicators applied for project selection generally considered maximum range of size differences between 20 and 25%.

Table 5: Definition of key performance indicators (criteria); reference units, weighting factors, and determination to target a higher or lower performance value

Key Performance Indicators—Project A; B	Total	Per trade	UoM	Adjustment Requirements/Remarks	Weightage Factor (ω_j') b	Category **
Project duration *	x	—	CW	Project comparation criteria—Δ < 20%	—	—
Gross floor area (GFA) *	x	x	m2	Project comparation criteria—Δ < 20%	—	—
Gross volume (GV) *	x	x	m3	Project comparation criteria—Δ < 20%	—	—
Construction costs *	x	x	€	Project comparation criteria—Δ < 20%	—	—
Average exceeding of construction units	x	—	%	considered: factoring errors by domino eff.	0.25	n-b
Value of cost overruns	x	x	€		0.25	n-b
Value of deadline exceedings	x	x	CW	classification: unprediced/customer wanted	0.15	n-b
Value of supplements/planning changes	x	x	€	classification: unprediced/customer wanted	0.1	n-b
No. of supplements/planning changes	x	x	No.		0.02	n-b
No. construction interruptions	x	x	No.		0.03	n-b
No. of disability complaints	x	x	No.		0.03	n-b
No. of default notifications	x	x	No.		0.03	n-b
No. of construction defects during execution	x	x	No.	classification: self-inflicted/not self-inflicted	0.02	n-b
No. of construction defects after handover	x	x	No.	classification: self-inflicted/not self-inflicted	0.02	n-b
Project commitment of stakeholdersstrongly disagree 1 |2 | 3 | 4 | 5 strongly agree	x	—	Grades	Grade system (*Likert-Scale* [49])	0.05	b
Injuries to workers	x	—	No.		0.05	n-b

* Criteria were used to determine the comparability of Project A and Project B. ** b ≙ beneficial—higher performance value is desired; n-b ≙ non-beneficial—lower performance value is desired.

8. Research Findings and Multi-Criteria Analysis

As comparing the two construction projects would have led to inaccuracies due to a lack of absolute equivalence, a reference value was introduced as a benchmark for data collection; this value was set to 1,000 m2 GFA (gross floor area). All measured values related to this factor. The planned duration of both projects, including planning, tendering, contracting, and execution, equaled nine months (Project A) and 11 months (Project B). To increase the two project`s comparability, both projects were divided into PSs of an approximately equal size. These sections were required to optimally allocate the scope of work and to serve as reference points for determining the project's process status indication.

Project B was completed within the planned construction period. Each construction section was also completed on time, so each predetermined milestone passed on time. Deviations caused by the estimated values determined during the project planning phase were compensated by the multi-flexible construction process organization. Moreover, implementing the enhanced 5D BIM approach contributed to a considerable reduction of the deviations between the as-planned and as-built values. Project A exceeded the planned end date with a delay of approximately four weeks. The project milestones were passed, on average, 3–5 days later than planned. This resulted in a shift of the entire schedule and caused the final deadline to be significantly exceeded. At first glance, Project B matched the budget; however, unexpected additional costs for necessary tablet/computer hardware and servers, including maintenance, hotline, and update services, were required to implement the new methodology. These costs amounted to a total of €22,825 net per 1,000 m2 per year for Project B. This resulted in an actual cost overrun of 6.04% for this project. The cost overrun of Project A equaled 16.2% in total for the reference value of 1,000 m2. This was caused by supplements due to inadequate planning, rework and defect management, and the extended construction period (extra costs for providing site equipment and staff).

To obtain a preliminary assessment of the new method's influence in terms of its enhancements to project performance, accuracy in project planning, and schedule and cost reliability, a multi-criteria analysis was conducted. Based on the two alternatives, Project A (i_A) and Project B (i_B), and the predefined analysis criteria (j_n) previously described by the KPIs (see Table 5), an evaluation matrix was developed (see Table 6). Here, the cell variables represent the project-based performance value (X_{ij}) of each criterion.

Table 6: Evaluation matrix – Determination of the performance value (X_{ij})

This method applies → $X_{ij} = performance\ value\ of\ the\ i^{th} alternative\ over\ the\ j^{th}\ criteria$

	j_1	j_2	j_3
i_A	$X_{i_A j_1}$	$X_{i_A j_2}$	$X_{i_A j_n}$
i_B	$X_{i_B j_1}$	$X_{i_B j_2}$	$X_{i_B j_n}$

To avoid assessment issues and to achieve comparable analysis results, the deviating units of measurement (UoM) for the criteria to be compared were unified, and linguistic classification terms were assigned to a number-based performance value scale. Furthermore, the analysis matrix had to be normalized which was required to obtain only numerical values without any units.

Next, each criterion was allocated into "beneficial—higher performance value is desired" (e.g., commitment of involved stakeholders) and "non-beneficial—lower performance value is desired" (e.g., exceeding final project deadline), and the normalized performance value (X'_{ij}) of each cell had to be calculated. For this purpose, the following formulas were applied based on the criteria classification "beneficial" or "non-beneficial." The minimum and maximum performance values were derived from the lowest and highest performance values of each criterion:

It applies → $X'_{ij}(beneficial) = \frac{X_{ij}}{Max\ (X_{ij})}$; $X'_{ij}(non - beneficial) = \frac{Min\ (X_{ij})}{X_{ij}}$.

Since the analysis matrix was normalized, a weighting factor (w'_j) was assigned to the normalized performance values (X'_{ij}) of each criterion ($\sum_{j=1}^{n} w'_j = 1$; see Table 6) to classify its influence on schedule and cost reliability, project planning accuracy, and project performance. Each normalized performance value was multiplied by the assigned weighted factor to obtain the weighted normalized analysis matrix.

To calculate the absolute performance scores of Project A and B, each weighted normalized performance value (X''_{ij}) of each project was cumulated. The entire calculation of the performance score per alternative ($[i_A]$ and $[i_B]$ [Project A; Project B]) can be described by the following formula:

$$performance\ score_{(i)} = \sum_{j=1}^{n} \left(\frac{x_{ij}}{Max\ (x_{ij})}\right) * w'_j + \sum_{j=1}^{n} \left(\frac{Min\ (x_{ij})}{x_{ij}}\right) * w'_j.$$

After collecting all measurement data related to the respective KPIs and evaluating all values, a total performance score of 0.38 was calculated for Project B. For Project A, the score equaled 0.12. To evaluate the significance of these values, the ranking scale presented in Table 7 was employed. This scoring model is generally applied to assess alternatives based on several quantitative and qualitative criteria, objectives, or conditions. Furthermore, this is used to analyze a set of complex alternatives to order the elements of the set according to the analysis preferences based on a multidimensional target system.

The order is represented by the performance value of each alternative. The evaluation numbers follow a five-fold scale (in this case, 0.05 to 0.55), where a higher evaluation number stands for a superior evaluation (see Table 7); (Likert 1932, Zangemeister 1970, Westermann and Finger 2012, Bautsch 2014).

Table 7: Ranking scale (JOCU 1985)

Scale Values	**Icon**	**Definition**
0.45–0.55	++	very good
0.35–0.449	+	good
0.25–0.349	0	sufficient
0.15–0.249	-	less sufficient
0.05–0.149	–	bad

As a result, according to the 5D-PROMPT method, Project B's planning and execution could generally be rated as "good". In direct comparison, Project A could only be rated as "bad" according to the conventional project planning and execution method. This indicates a considerable improvement to construction planning and execution in accordance with the 5D-PROMPT method and represents an immense enhancement of the overall project performance.

Further results and differences regarding both project organization methods are listed and explained in the following section.

The comparison further indicated that the number of construction defects during the construction phase of Project B was 82.6% lower than of Project A. The costs for supplements and changes in planning due to customer voice were also approximately 71.5% lower than those in the comparable project. The participant's commitment to the newly introduced method of Project B was rather high (Grade 5 – "Strongly agree" from the Likert scale analysis [Likert 1932]), but the project execution team's commitment to the conventional method was also rated “high” (Grade 4 – "Agree" from the Likert scale analysis [Likert 1932]). The number of hold-up notifications (notices of delay) and notices of default yielded three in total for Project A while Project B remained completely unaffected by these measures.

There was no absolute stop of construction work in either project. Moreover, an officially decreed construction stop was imposed in neither of the projects, and no workers were injured or killed during the construction process. The costs of implementing the new methodology for Project B related to the following services: (1) Introduction and training in the project organization method, (2) software teaching and training, (3) process consulting, (4) development of project-relevant master data, and (5) operational project support. These services were calculated proportionately according to the reference values of 1,000 m2 per year and amounted to €38,500 net in total. These costs include, as described above, the considerable additional costs for extra required hardware equipment and software-related services.

8. Hallazgos de la investigación y análisis multicriterio

Dado que la comparación de los dos proyectos de construcción habría dado lugar a inexactitudes debido a la falta de equivalencias absolutas, se introdujo un valor de referencia para la recopilación de datos; este valor se fijó en 1.000 m2 de superficie bruta (GFA, por sus siglas en inglés). Todos los valores medidos se relacionan con este factor. La duración prevista de ambos proyectos, incluida la planificación, la licitación, la contratación y la ejecución, fue de 9 meses (Proyecto A) y 11 meses (Proyecto B). Para aumentar la comparabilidad de los dos proyectos, ambos se dividieron en secciones de proyecto de un tamaño aproximadamente igual. Estas secciones eran necesarias para asignar de manera óptima el alcance de la labor y servir como puntos de referencia para determinar el estado del proceso del proyecto.

El proyecto B se completó dentro del período de construcción previsto. Cada sección de la construcción también se completó a tiempo, por lo que cada hito predeterminado concluyó a tiempo. Las desviaciones causadas por los valores estimados que fueron determinados durante la fase de planificación del proyecto fueron compensadas por la ágil organización multi-flexible del proceso de construcción. Además, la aplicación del enfoque mejorado 5D BIM contribuyó a una reducción considerable de las desviaciones entre los valores de cómo se planificó y cómo finalmente se construyó. El Proyecto A excedió la fecha de finalización prevista con un retraso de aproximadamente cuatro semanas. Los hitos del proyecto se excedieron, en promedio, de 3 a 5 días por sobre lo previsto. Esto dio lugar a un cambio en todo el calendario y provocó que se superara considerablemente la fecha límite final. A primera vista, el Proyecto B se ajustó al presupuesto; sin embargo, para aplicar la nueva metodología se necesitaron gastos adicionales no planeados para el equipo y las redes de tablets y ordenadores necesarios, incluidos servicios de mantenimiento, línea telefónica directa y actualizaciones. Estos costes ascendieron a un total de 22.825 euros netos por cada 1.000 m2 al año para el Proyecto B, lo que dio lugar a un sobrecoste real del 6,04% para este proyecto. El sobrecoste del Proyecto A equivalía a un 16,2% en total para el valor de referencia de 1.000 m2. Esto fue causado por los suplementos debidos a la planificación inadecuada, el re-trabajo y la gestión de los defectos, y el prolongado período de construcción (costes adicionales para el suministro de equipo y personal del sitio).

Para obtener una evaluación preliminar de la influencia del nuevo método en lo que respecta a sus mejoras en el rendimiento de los proyectos, la precisión en la planificación de los proyectos y la confiabilidad de los cronogramas y los costos, se realizó un análisis multicriterio. Sobre la base de las dos alternativas, el Proyecto A (i_A) el Proyecto B (i_B)y los criterios de análisis predefinidos (j_n) previamente descrita por los KPI (ver Tabla 5). Se desarrolló una matriz de evaluación (ver Tabla 8). Aquí, las variables de la celda representan el valor de rendimiento basado en el proyecto (X_{ij}) de cada criterio.

Tabla 8: Matriz de evaluación - Determinación del valor de rendimiento (X_{ij})

Este método se aplica → $X_{ij} = rendimiento\ valor\ de\ el\ i^{th} alternativa\ sobre\ el\ j^{th}\ criterios$

	j_1	j_2	j_3
i_A	$X_{i_A j_1}$	$X_{i_A j_2}$	$X_{i_A j_n}$
i_B	$X_{i_B j_1}$	$X_{i_B j_2}$	$X_{i_B j_n}$

Para evitar problemas de evaluación y lograr resultados de análisis comparables, se unificaron las unidades de medida desviadas (UM) de los criterios que se iban a comparar, y se asignaron términos de clasificación lingüística a una escala de valores de rendimiento basada en números. Adicionalmente, se tuvo que normalizar la matriz de análisis, lo cual fue necesario para obtener sólo valores numéricos sin ninguna unidad.

A continuación, cada criterio se asignó a "beneficioso - se desea un valor de rendimiento más alto" (por ejemplo, el compromiso de los implicados en el proyecto) y "no beneficioso - se desea un valor de rendimiento más bajo" (por ejemplo, exceder el plazo final del proyecto), y el valor de rendimiento normalizado (X'_{ij}) de cada celda tuvo que ser calculada. Para ello se aplicaron las siguientes fórmulas basadas en la clasificación de los criterios "beneficioso" o "no beneficioso". Los valores de rendimiento mínimo y máximo se derivaron de los valores de rendimiento más bajo y más alto de cada criterio:

Se aplica → $X'_{ij}(beneficioso) = \frac{X_{ij}}{Max\ (X_{ij})}; X'_{ij}(no\ beneficioso) = \frac{Min\ (X_{ij})}{X_{ij}}.$

Después de normalizar la matriz de análisis, se asignó un factor de ponderación (w'_j) a los valores de rendimiento normalizados (X'_{ij}) de cada criterio ($\sum_{j=1}^{n} w'_j = 1$ (véase la Table 6) para clasificar su influencia en la fiabilidad de los plazos y los costes, la precisión de la planificación del proyecto y el rendimiento del mismo. Cada valor de rendimiento normalizado se multiplicó por el factor ponderado asignado para obtener la matriz de análisis normalizado ponderado.

Para calcular las puntuaciones absolutas de rendimiento del Proyecto A y B, se acumularon los valores del rendimiento normalizado ponderado (X''_{ij}) de cada proyecto. Todo el cálculo de la puntuación de rendimiento por alternativa ([i_A] y [i_B] [Proyecto A; Proyecto B]) puede describirse mediante la siguiente fórmula:

$$puntuación\ de\ rendimiento_{(i)} = \sum_{j=1}^{n} \left(\frac{X_{ij}}{Max\,(X_{ij})}\right) * w'_j + \sum_{j=1}^{n} \left(\frac{Min\,(X_{ij})}{X_{ij}}\right) * w'_j.$$

Después de recopilar todos los datos de medición relacionados con los respectivos KPI y analizar todos los valores, se calculó una puntuación total de rendimiento de 0,38 para el Proyecto B. En el caso del Proyecto A, la puntuación fue de 0,12. Para evaluar la importancia de estos valores, se empleó la escala de clasificación presentada en la Tabla 10. Este modelo de puntuación se aplica generalmente para evaluar alternativas basadas en diferentes criterios, objetivos o condiciones cuantitativos y cualitativos. Además, se utiliza para analizar un conjunto de alternativas complejas para ordenar los elementos del conjunto de acuerdo con las preferencias de análisis basadas en un sistema de objetivos multidimensionales.

El orden está representado por el valor de rendimiento de cada alternativa. Los números de evaluación siguen una escala de cinco niveles (en este caso, de 0,05 a 0,55), en la que un número de evaluación mayor representa una evaluación superior (véase la 9); (Likert 1932, Zangemeister 1970, Westermann y Finger 2012, Bautsch 2014).

Tabla 9: Escala de clasificación (JOCU 1985)

Scale Values	Icon	Definition
0.45–0.55	++	very good
0.35–0.449	+	good
0.25–0.349	0	sufficient
0.15–0.249	-	less sufficient
0.05–0.149	–	bad

Como resultado, según el método 5D-PROMPT, la planificación y ejecución del Proyecto B podría calificarse en general como "buena". En comparación directa, el Proyecto A sólo podía calificarse como "malo" según el método convencional de planificación y ejecución de proyectos. Esto indica una mejora considerable en la planificación y ejecución de la construcción de acuerdo con el método 5D-PROMPT y representa una inmensa mejora en el rendimiento global del proyecto. En la siguiente sección se enumeran y explican otros resultados y diferencias relativos a ambos métodos de organización del proyecto.

La comparación indicó además que el número de defectos de construcción durante la fase de construcción del Proyecto B fue un 82,6% inferior al del Proyecto A. Los costos de los suplementos y los cambios de planificación debidos a la solicitud del cliente también fueron aproximadamente un 71,5% inferiores a los del proyecto comparable. El compromiso de los participantes con el método recientemente introducido del Proyecto B fue bastante alto (Grado 5 - Muy de acuerdo del análisis de la escala de Likert [Likert 1932]), pero el compromiso del equipo de ejecución del proyecto con el método convencional también se calificó de "alto" (Grado 4 - De acuerdo del análisis de la escala de Likert [Likert 1932]). El número de notificaciones de discapacidad (avisos de retraso) y de notificaciones de incumplimiento ascendió a tres en el Proyecto A, mientras que el Proyecto B no se vio afectado en absoluto por estas medidas.

No hubo un paro absoluto de los trabajos de construcción en ninguno de los dos proyectos. Además, en ninguno de los proyectos se impuso un paro de la construcción decretada oficialmente, y ningún trabajador resultó herido o muerto durante el proceso de construcción. Los costos de la aplicación de la nueva metodología para el Proyecto B se relacionaron con los siguientes servicios: 1) Presentación y capacitación en el método de organización de proyectos, 2) enseñanza y capacitación en materia de programas informáticos, 3) consultoría de procesos, 4) elaboración de datos maestros pertinentes para el proyecto y 5) apoyo operacional al proyecto.

Estos servicios se calcularon proporcionalmente según los valores de referencia de 1.000 m2 por año y ascendieron a 38.500 euros netos en total. Estos costos incluyen, como se ha descrito anteriormente, los gastos considerables adicionales de equipo de hardware y servicios relacionados con el software que se requieren de manera adicional.

9. Discussion

The initially mentioned productivity growth in the American and European construction sectors has indicated significant structural weaknesses and considerable performance deficiencies over a long period of time. The two graphs presented at the beginning of this work (see Figure 5 and Figure 6) clearly illustrate the differences between the conditions of the overall economy compared to those of the construction industry.

Nevertheless, the American as well as the European markets encompass a large share of the global economic sector but represent only a portion of the overall international situation. As such, further statistics and additional information could have been included in this section. However, this was decided in this case, since the literature study provides further and more detailed information on this subject. Moreover, this provides a relatively far-reaching overview of the previous and current specific root causes of errors that predominate in the construction industry.

One problem that became apparent in the literature study concerned the fact that many of the studies followed rather different approaches, making them difficult to compare with each other. Furthermore, some studies or approaches did not refer to the entire cycle of a construction project, but instead only covered a specific part or even just a particular phase of a building project. As such, the 5D-PROMPT method was intended to meet the requirements of the overall construction project lifecycle.

Within the concept of the 5D-PROMPT method, a 5D building information model (BIM) was implemented as a SSOT. The project timeframe (project start/end date) and key milestones were determined and optimized via 5D construction process simulation and subsequently transferred to the construction execution phase in order to establish a basic grid for the multi-flexible execution organization. Onsite activities were managed by teamwork in accordance with agile principles. In addition, knowledge gained from construction execution was reported back to the project planning phase for application in future project planning. Thus, it can be stated the 5D-PROMPT method provides a coherent approach to optimizing a complete construction project process. It is composed of different project management and schedule methods that are already known and have previously been successfully applied. Nevertheless, the system of the composed individual approaches in this particular manner generates considerable potential for improvements. Despite this, the presented approach does not inevitably represent the end of the optimization development. According to the lean principle “Seeking Perfection,” this system can and must be further optimized and advanced.

The project organization method, referred to as the common method in this thesis, should only be understood as an example and represents only one of countless other possible examples. Nevertheless, it was important to present the advantages and improvements of the 5D-PROMPT method based on a project method previously known and widely used in practice.

The comparative case study was conducted to obtain a preliminary and brief overview regarding possible improvements to project performance, project planning accuracy, and scheduling/cost reliability by applying the 5D-PROMPT method. It should not be seen as a representative study, as only one sample for each criterion/alternative could be collected due to comparing only two projects. Nevertheless, a range of different KPIs (criteria) were measured, providing the study results a certain significance. For the comparability of both projects, it was of particular importance that both projects were appropriately similar (max Δ < 20–25%) and were simultaneously conducted by the same executing company. For this purpose, the PROMPT Administration Board was used as an analog planning board within the case study. To avoid interface problems or possible loss of information in future investigations, a digital planning board, fully integrated into the overall process, would be required. Automated functions based on a self-learning system should also be developed in future papers.

A main obstacle that emerged when implementing the project under the 5D-PROMPT method (Project B) involved defining the TU`s content and the corresponding model objects. A general trade-by-trade definition was considered unusable, since different trade specifications feature various completion characteristics in terms of (a) the standardization of target unit measurements, (b) increasing deviations over long project execution periods, and (c) tracking of multiple correlated design changes. These issues were solved by classifying and aligning trade-compliant model sections, which were measurable, de-limitable, and directly extractable from the 5D BIM. This common problem (typical for multi-flexible organized projects with missing references for project target dates, deadlines, or time limits) was handled by properly determined project start/end dates and PS-related milestones. In this way, the course and frame of the project followed a clear structure and was traced by the participating stakeholders. To solve resultant coordination difficulties, the foremen of adjacent trades took part in agile organization meetings and contributed to solving forthcoming issues.

The case study results indicated considerable improvement in the pursued objectives. However, since only one project was counted as a sample, this study was relatively limited. Therefore, no statistical evaluation of the results was achievable. However, due to the large number of different criteria examined, it was possible to conduct a multi-criteria analysis to provide a preliminary impression of this method's effectiveness. Weighing the multi-criteria analysis was particularly focused on the criteria that affect exceeding construction time and costs, as well as disruption-free construction processes. One experienced value concerns the oversized storage capacity of the server used for Project B. In future projects, this value could be considerably reduced, thereby decreasing the direct project costs per 1,000 m2.

Generally, the proposed method's technical implementation and feasibility was proven to be beneficial, and possible technical improvements have already been derived. To obtain a reliable evaluation of the effects of the entire 5D-PROMPT method, a series of projects must be conducted and examined in accordance with this method in future investigations.

9. Discusión

El crecimiento de la productividad mencionado inicialmente en los sectores de la construcción de América y Europa ha mostrado importantes debilidades estructurales y deficiencias considerables en el rendimiento de los trabajos del sector de la construcción durante un largo período. Los dos gráficos presentados al principio de este trabajo (véase la Figure 5 y la Figure 6) ilustran claramente las diferencias entre las condiciones de la economía general en comparación con las de la industria de la construcción.

Aunque los mercados estadounidense y europeo abarcan una gran parte del sector económico mundial, representan sólo una parte de la situación internacional general. Por ello, en esta sección se podrían haber incluido más estadísticas e información adicional. Sin embargo, así se decidió en este caso, ya que el estudio del estado del arte proporciona información adicional y más detallada sobre este tema. Además, proporciona un panorama relativamente amplio de las causas fundamentales específicas, anteriores y actuales, de los errores que predominan en la industria de la construcción.

Un problema que se puso de manifiesto en el estudio de la literatura se refiere al hecho de que muchos de los estudios seguían enfoques bastante diferentes, lo que hacía difícil compararlos entre sí. Además, algunos estudios o enfoques no se referían al ciclo completo de un proyecto de construcción, sino que sólo abarcaban una parte específica o incluso sólo una fase particular de un proyecto de construcción. Así pues, el método 5D-PROMPT tenía por objeto cumplir los requisitos del ciclo de vida general del proyecto de construcción.

Dentro del concepto del método 5D-PROMPT, se implementó un modelo de información de construcción 5D (BIM) como un SSOT. El marco temporal del proyecto (fecha de inicio/fin del proyecto) y los hitos clave fueron determinados y optimizados a través de la simulación del proceso de construcción 5D y posteriormente transferidos a la fase de ejecución de la construcción con el fin de establecer una red básica para la organización ágil de la ejecución. Las actividades in-situ se gestionaron mediante el trabajo en equipo de acuerdo con los principios de la metodología multi-flexible. Además, los conocimientos adquiridos durante la ejecución de la construcción se comunicaron a la fase de planificación del proyecto para su aplicación en la planificación de proyectos futuros. Así pues, puede afirmarse que el método 5D-PROMPT proporciona un enfoque coherente para optimizar un proceso completo del proyecto de construcción. Está compuesto por diferentes métodos de gestión y programación de proyectos que ya se conocen y que se han aplicado con éxito anteriormente. Sin embargo, el sistema de enfoques individuales compuestos en esta particular manera, genera un potencial considerable de mejoras. A pesar de ello, el enfoque presentado no representa inevitablemente el final del desarrollo de la optimización. De acuerdo con el principio *lean* "Buscando la perfección", este sistema puede y debe ser optimizado y avanzado aún más.

El método de organización de proyectos, denominado método común en este artículo sólo debe entenderse como un ejemplo y representa sólo uno de otros innumerables ejemplos posibles. No obstante, es importante presentar las ventajas y mejoras del método 5D-PROMPT basado en un método de proyecto previamente conocido y ampliamente utilizado en la práctica.

El estudio de caso comparativo se realizó para obtener una visión general preliminar y breve sobre las posibles mejoras en el rendimiento del proyecto, la precisión de la planificación del proyecto y la fiabilidad de la programación de obra y el coste mediante la aplicación del método 5D-PROMPT. No debe considerarse como un estudio representativo, ya que sólo se pudo recoger una muestra para cada criterio/alternativa debido a la comparación de sólo dos proyectos. No obstante, se midieron una serie de diferentes KPI (criterios), lo que dio cierta relevancia a los resultados del estudio. Para la comparación de ambos proyectos, fue de particular importancia que los dos proyectos fueran aproximadamente similares (máx. $\Delta < 20\text{-}25\%$) y que fueran realizados simultáneamente por la misma empresa ejecutora. Con ese fin, se utilizó la Junta de Administración del PROMPT como junta de planificación análoga dentro del estudio de casos. Para evitar problemas de interfaz o posibles pérdidas de información en investigaciones futuras, se necesitaría una junta de planificación digital, plenamente integrada en el proceso general. Se deberían también desarrollar funciones automatizadas basadas en un sistema de autoaprendizaje en estudios futuros.

Uno de los principales obstáculos que surgieron al implementar el proyecto bajo el método 5D-PROMPT (Proyecto B) fue la definición del contenido de las unidades de trabajo y los objetos del modelo correspondientes. Se consideró que una definición general de actividad por actividad no era útil, ya que las diferentes especificaciones de las diferentes actividades presentan diversas características de terminación en términos de: a) la estandarización de la medida de las unidades objetivo, b) el aumento de las desviaciones durante largos períodos de ejecución del proyecto, y c) el seguimiento de los cambios de diseño múltiples correlacionados. Estos problemas se resolvieron clasificando y alineando las secciones del modelo que cumplían con el oficio en cuestión, que eran medibles, delimitables y directamente extraíbles de la 5D BIM. Este problema común (típico de los proyectos organizados de forma multi-flexible, con falta de referencias para las fechas objetivo del proyecto, plazos o límites de tiempo) fue manejado por las fechas de inicio/fin del proyecto y los hitos relacionados con las secciones de proyecto apropiadamente determinados. De esta manera, el curso y el marco del proyecto siguieron una estructura clara y fueron trazados por los participantes. Para resolver las dificultades de coordinación resultantes, los capataces de los oficios adyacentes participaron en reuniones de organización multi-flexible y contribuyeron a resolver los asuntos venideros.

Los resultados del estudio de casos indicaron una mejora considerable de los objetivos buscados. Sin embargo, como sólo se contó con un proyecto como muestra, este estudio fue relativamente limitado. Por consiguiente, no se pudo realizar una evaluación estadística de los resultados. No obstante, debido al gran número de criterios diferentes examinados, fue posible realizar un análisis multicriterio para dar una impresión preliminar de la eficacia de este método. La ponderación del análisis multicriterio se centró particularmente en los criterios que afectan al tiempo y los costos de construcción excedentes, así como a los procesos de construcción sin interrupciones. Uno de los valores experimentados se refiere a la capacidad de almacenamiento sobredimensionada del servidor utilizado para el Proyecto B. En futuros proyectos, este valor podría reducirse considerablemente, disminuyendo así los costos directos del proyecto por cada 1.000 m2.

En general, se demostró que la aplicación técnica y la viabilidad del método propuesto fueron beneficiosas, y ya se han obtenido posibles mejoras técnicas. Para obtener una evaluación fiable de los efectos de todo el método 5D-PROMPT, se deben llevar a cabo una serie de proyectos y examinarlos de acuerdo con este método en futuras investigaciones.

10. Conclusions

10.1. General Conclusions

With this study it was shown that construction projects, which were designed and implemented in accordance with the newly developed 5D-PROMPT method, could be considerably improved in terms of adherence to schedules and cost reliability, as well as to the overall project performance. This was initially demonstrated by the results of a comparative case study. Thus, through the holistic approach a system was created, that successfully interconnects all phases of a construction project. Moreover, it was proven, that the general and individual requirements of each project phase have been optimally addressed and fulfilled by the structure of the new method.

The previously determined deficiencies in construction design and execution organization as well as the continuously ongoing project schedule and budget exceedings, that were exposed and summarized at the outset of this study have been considered comprehensively by the new approach. Through the following key principles, specific solution approaches were given – in response to the individual problem statements - which in their entirety characterize the general process-structure of the 5D-PROMPT method:

- Utilization of the 5D BIM methodology for all design targets
- IT-supported interconnection of the 3D BIM objects with the associated schedule activities and corresponding cost positions
- Virtual 5D construction process simulation (waterfall-based)
- Multi-flexible and team-based work execution organization
- Determination, evaluation and feedback of as-planned / as-built deviations
- Persistent? project status indications (highlighted by the individual 5D model objects in accordance to the current statuses of completition)

By the interconnection of the 3D BIM elements with the corresponding schedule and cost positions in the design phase, it was shown that the application of the 5D BIM methodology has significantly contributed to a solid connection between the elements of the project model and the associated construction costs as well as execution activities. In this way, the possible discrepancies and drifting-apart of the design elements, construction durations and costs were already prevented in the construction planning phase. This type of linkage was capable to provide a close dependency between the design objects and the associated construction times and costs even until the completion of the construction work.

Moreover, the project schedule, which was strictly hierarchical and chronologically structured throughout the design phase, has enabled a 5D BIM-based simulation of the construction process on this basis. From this, important scheduling events could be derived, which were used as a leading structure for an agile work execution organization. Through the implementation of this process-sequence the multi-flexible execution organization has enabled the crucial flexibility needed for the organization and execution of the work on the construction site. In addition, the implementation of the continuous improvement process has enabled a sustainable optimization of the planning foundations for future projects.

10.2. Specific Conclusions

The considerable potential of improvement of the 5D-PROMPT method has been demonstrated by means of a comparative case study in which one project (A) was carried out according to a conventional construction planning and execution method and one project (B) according to the new method. By the application of the new principles, the performance score, which was measured and evaluated using specially selected key performance indicators, has been improved from 0.12 to 0.32 (Ranking Scale: 0.05 - 0.55). Furthermore, this project (B) was completed within the given time frame and moreover all project milestones (events) have been passed without any delay. In comparation, the average delay of project (A) was at 3-5 days per each Project Section. The provided process steps resulted in a significant increase in the overall performance of project (B), which can be traced back to the utilization of the 5D-PROMPT method.

It is of particular importance at this point to mention that project (A) has neither been completed before nor after the planned delivery dates, which already points to an improved interaction between the project design process and the agile organization of the construction execution process. The implementation of the new method was aimed to achieve this target, since only the exact adherence to the schedule ensures a high precision of future scheduling. The overrun of the total project costs has been reduced from 16.2% (Project A) to 6% (Project B), whereby the cost overrun in Project B was primarily caused by the implementation effort of the new method. It can be assumed that these costs can still be reduced significantly in future projects.

By the feedback of information, which resulted from determined deviations of the target/actual values between construction planning and execution activities, previously applied time-based effort values could be optimized. However, improvements based on this process steps have yet not been considered in the current case study.

In general, it can be comprehended that the application of the 5D-PROMPT method can lead to significant increasements in project performance, as well as considerable improvements in cost and schedule reliability. However, since the method was only implemented and tested initially in this study, it has not yet been possible to make a final statement about the overall improvement potential. In order to generate valid results, the method must be applied and tested in a variety of further studies.

As an important note, with regard to the accelerated digitization and implementtion of IT-supported systems in the construction sector, it should be pointed out that this in turn fundamentally increases the susceptibility to disruptions caused by system-dependent error sources, viruses or cyber attacks. As the structure of the 5D-PROMPT method is mainly based on the use of software-based applications as well as web-based data exchanges it is indispensable to ensure appropriate IT-security measures and regularly conducted system/data backups.

10. Conclusiones

10.1. Conclusiones Generales

Con este estudio se ha mostrado que los proyectos de construcción, que fueron diseñados e implementados de acuerdo con el método recientemente desarrollado 5D-PROMPT, podrían mejorar considerablemente desde el punto de vista de la planificación y confiabilidad de los costes, así como en la gestión general del proyecto. Esto fue inicialmente demostrado por los resultados de un estudio comparativo de caso. Por lo tanto, a través de un enfoque integral se ha creado un sistema que exitosamente interconecta todas las fases de un proyecto de la construcción. Además, se ha probado que los requisitos generales e individuales de cada fase del proyecto han sido abordados exitosamente y cumplidos por la estructura del nuevo método.

Las deficiencias previamente determinadas en el diseño de la construcción y la organización de la ejecución así como la planificación del proyecto en curso y sobrepasos de presupuesto continuos, que fueron expuestos y resumidos al comienzo de este estudio han sido considerados de forma exhaustivo por el nuevo enfoque. A través de los siguientes principios clave, se han dado enfoques de solución específicos -en respuesta a las formulaciones al problema individual- que en su totalidad caracterizan la estructura de proceso general del método 5D-PROMPT:

- Utilización de la metodología 5D BIM para todos los objetivos de diseño
- Interconexión con soporte de TI de los objetos de 3D BIM con el calendario de actividades asociadas y sus correspondientes posiciones de coste
- Construcción 5D virtual del proceso de simulación de la construcción (basada en el modelo “cascada”)
- Organización de la ejecución de la obra multi-flexible y basada en equipos
- Determinación, evaluación y retroalimentación de desviaciones según lo planeado y según lo construido
- Indicaciones de estatus del proyecto persistentes (resaltadas por los objetos del modelo 5D de acuerdo a los nuevos estatus de completación actuales)

Por la interconexión de los elementos 3D BIM con su correspondiente calendario y posiciones de coste en la fase de diseño se ha mostrado que la aplicación de la metodología 5B BIM ha contribuido significativamente a una conexión sólida entre los elementos del modelo de proyecto y los costes asociados así como a las actividades de ejecución. De esta manera, las posibles discrepancias y distanciamiento de los elementos de diseño, duración y coste de la construcción han sido evitadas ya en la fase de planificación de la construcción. Este tipo de enlace fue capaz de proporcionar una dependencia cercana entre los objetos de diseño y los tiempos y costes asociados de la construcción incluso hasta la completación de la obra de construcción.

Además, el calendario del proyecto, que estaba estrictamente y jerárquicamente estructurado a través de la fase de diseño, ha permitido una simulación 5D basada en la simulación del proceso de la construcción sobre esta base. A partir de aquí, se pudieron derivar eventos de calendario importantes, que fueron usados como estructura destacada para una organización de la ejecución de obra ágil. A través de la implementación de esta secuencia del proceso la organización de la ejecución multi-flexible ha permitido la flexibilidad crucial necesaria para la organización y ejecución de la obra en el lugar de la obra. Asimismo, la implementación del proceso de mejora continuo ha permitido una optimización sostenible de las bases de la planificación para proyectos futuros.

10.2. Conclusiones específicas

El considerable potencial de mejora del método 5D-PROMPT ha sido demostrado por medio de un caso de estudio comparativo en el cual un proyecto (A) fue llevado a cabo de acuerdo a un nuevo método. Por la aplicación de los nuevos principios, el puntaje del desempeño, que fue medido y evaluado usando indicadores de desempeño claves, ha sido mejorado de 0.12 a 0.32 (Escala de Ranking: 0.05 – 0.55). Es más, este proyecto (B) fue completado dentro del marco de tiempo dado e incluso todos los hitos del proyecto (eventos) han sido aprobados sin demora. En comparación, el retraso medio del proyecto (A) fue de 3-5 días por cada Sección del Proyecto. Las etapas de proceso resultaron en un aumento significativo en el desempeño general del proyecto (B), el cual puede ser trazado hasta la utilización del método 5D-PROMPT.

Es de particular importancia en este momento mencionar que el proyecto (A) no ha sido completado ni antes ni después de las fechas de entrega, lo cual apunta a una interacción mejorada entre los procesos de diseño del proyecto y la organización ágil de los procesos de ejecución de la construcción. La implementación del nuevo método esta dirigida a alcanzar este objetivo, debido a que solo el apego exacto al calendario asegura una alta precisión del calendario futuro. El sobrecoste de costes del proyecto total se ha reducido de 16.2% (Proyecto A) a 6% (Proyecto B), por el que el sobrecoste en el Proyecto B fue causado principalmente por la implementación del nuevo método. Se puede asumir que estos costes todavía se pueden reducir significativamente en proyectos futuros.

Por la retroalimentación de información, que resultó de las desviaciones determinadas por los valores objetivo/realidad entre la planificación de la construcción y actividades de ejecución, valores de esfuerzo basados en el tiempo aplicado podrían ser optimizados. Sin embargo, mejoras basadas en las etapas de este proceso no han sido consideradas todavía en el presente estudio de caso.

En general, se puede comprender que la aplicación del método 5D-PROMPT puede llevar a la mejora significativo del desempeño de un proyecto, así como a considerables mejoras de coste y confiabilidad del calendario. Sin embargo, debido a que este método fue solo implementado y probado con este estudio, no ha sido posible todavía hacer una declaración final sobre el potencial de mejora general. Para generar resultados válidos, el método debe ser aplicado y probado en una variedad de estudios adicionales.

Como nota importante, de acuerdo a la digitalización e implementación de sistemas basados en interconexión con soporte TI en el sector de la construcción, se debe puntualizar que esto a su vez aumenta de manera evidente la susceptibilidad a alteraciones causadas por fuentes de error basadas en sistemas, virus o ciber ataques. Como la estructura del método 5D-PROMPT está principalmente basada en el uso de aplicaciones basadas en software así como en intercambios de datos basados en la web es indispensable asegurar las medidas de seguridad de TI y regularmente revisar y actualizar copias de seguridad de los sistemas y de los datos.

11. Future Research Lines

- Further studies and empirical analyses are required to evaluate the possible potential of improvement of the overall 5D-PROMPT method in terms of:
    - schedule reliability,
    - cost adherence as well as
    - possible improvements in project management, and
    - long-term optimization of the planning accuracy.

- Continuously processed research must be conducted over a period of several years to evaluate the sustainability of enhancements caused by the implementation of the new approach.

- Deeper research is required to investigate if the application of the continuous improvement process has the aspired result and contributes to persistent adjustments of the dataset of cost and time-related effort values.

- It has to be proven when implementing the continuous improvement process, that deviations between construction planning and execution are constantly minimized.

- It must be determined for which type of construction project the method can best be applied and which is the optimum project size in terms of construction costs and project duration in order to gain the maximum benefit of the 5D-PROMPT method.

- Further research is necessary to work out how the transference of information from the waterfall-based construction schedule can be transferred to the multi-flexible planning board in the best possible and fully automated way.

- On the current occasion of the Covid 19 pandemic - which affects all areas of public and private life, as well as all conceivable economic and industrial sectors - specially designed studies should be carried out, in order to investigate the potential of prevention of the 5D-PROMPT method regarding impending schedule or cost explosions due to logdown/quarantine or similar requirements.

11. Futuras líneas de investigación

- Es necesaria la realización de estudios adicionales y análisis empíricos para evaluar el posible potencial de mejora general del método 5D_PROMPT desde el punto de vista de:
    - confiabilidad de la planificación,
    - apegos a los costes así como
    - mejoras posibles en la gestión del proyecto, y
    - optimización a largo plazo de la precisión de la planificación.

- Se debe efectuar una investigación procesada de forma continuada durante un período de varios años para evaluar la sostenibilidad de las mejoras provocadas por la implementación del nuevo enfoque.

- Es necesario realizar una investigación más profundizada si la aplicación del proceso de mejora continuo tiene los resultados esperados y contribuye a los ajustes persistentes del conjunto de datos de valores de coste y esfuerzos relacionados con el tiempo.

- Se debe verificar al momento de implementar el proceso de mejora continuada que las desviaciones entre la planificación de la construcción y su ejecución son minimizadas de forma constante.

- Se debe determinar para qué tipo de proyecto de construcción se adecúa mejor la aplicación del método y cuál es el tamaño óptimo de proyecto en relación con los costes de construcción y duración del proyecto de manera de conseguir el máximo beneficio del método 5D-PROMPT.

- Es necesaria una nueva investigación para resolver cómo la transferencia de información de la programación basada en escala puede ser transferida a la junta de planificación multi-flexible de la mejor y más automatizada forma posible.

- Con motivo de la pandemia de la Covid 19 – que afecta todas las áreas de la vida pública y privada, así como a todos los sectores económicos e industriales – se deberían realizar estudios especialmente diseñados para investigar el potencial de prevención del método 5D-PROMPT en relación al calendario amenazado o explosión de costes debido a confinamientos/cuarentenas u otras circunstancias

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Annex

Leicht, D., Castro-Fresno, D., Dìaz, J., Baier, C., (2020), "Multidimensional Construction Planning and Agile Organized Project Execution - The 5D-PROMPT Method", MDPI, Basel, Switzerland, Sustainability, 12(16), 6340; Sustainability, doi:10.3390/su12166340

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Article

Multidimensional Construction Planning and Agile Organized Project Execution—The 5D-PROMPT Method

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Abstract: Although tremendous technological and strategic advances have been developed and implemented in the construction sector in recent years, there is substantial room for improvement in the areas of productivity growth, project performance, and schedule reliability. Thus, the present paper seeks to discover why the currently applied scheduling tools and the latest agile-based project organization approaches have not yet achieved their full potential. A missing interlinkage between the project's design, cost, and time aspects within the project design phase and its sparse utilization throughout project execution were indicated as the driving contributors responsible for the slow progress in development. To fundamentally change this situation, an extensive and coherent project organization solution is proposed. The key process of this solution utilizes a 5D Building Information Model comprising tight concatenations between the individual model objects and the corresponding construction cost and time effort values. The key dates of a waterfall-based construction process simulation, set during the project planning phase, provide particular information to create a structure for agile organized project execution. The implementation of information feedback loops allows target/actual comparisons and contributes to continual improvements in future planning. A comparative case study was conducted with auspicious results on improvements in the overall project performance, and schedule and cost reliability.

Keywords: 5D building information modeling; agile project organization; schedule/cost reliability

1. Introduction

Large-scale construction projects are multi-faceted systems of complex and dynamic processes, which are constantly subjected to a multitude of internal and external influencing factors [1]. Tight time and budget constraints and increasing technical demands create challenging conditions to keep projects within their envisaged timeframes [2]. Insufficient limitations on design changes in later project stages, due to customer requests, increase the risk of postponements and growing time issues. Furthermore, the applied schedules often do not meet project-specific process requirements, frequently run out of time, and are exceeded or totally disregarded. In this way, projects are considerably delayed, costs run out of control, and the failure of the project becomes foreseeable [2–4].

In contrast to other industrial sectors, the construction industry has struggled to achieve high productivity rates over the past years. The contributing factors are manifold and have inimically affected not just national market conditions but the global construction economy as a whole [5–7]. This trend is evidenced by the productivity ratings (gross value added at constant prices) that were continuously recorded between 1995 and 2019 by the statistic department of the Organization for

Economic Cooperation and Development (OECD) (comparable EU/US data are provided by the OECD only between 1995 and 2017). During this time, the average annual productivity growth of the European construction sector was at 0.1%, while the average U.S. value was −0.2%. Compared to the total economy, these values indicate an average deviation of 1.6% in the EU and 2.3% in the US [8].

The annual productivity values of the construction sector in the U.S. increased between 2012 and 2019, highlighting the responsible factors for the error-triggering liabilities in the construction sector. According to the results of many investigations, the tenuous development of the construction industry can be traced back to inefficient working methods. This conclusion is evidenced in Figures 1 and 2, whereupon the efficiency of an economic sector is expressed by the ratio between its aggregated input and output values (based on equivalent and comparable factors (e.g., growth per gross domestic product (GDP), gross value added (GVA), total hours worked, unit labor costs) concerning deviating factors, different activity segments, deflators, and exchange rates) [9].

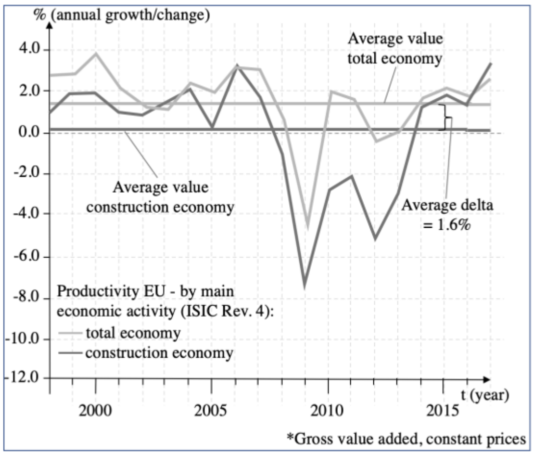


Figure 1. Annual productivity ratings of the EU; total economy vs. construction economy; Figure based on [10].

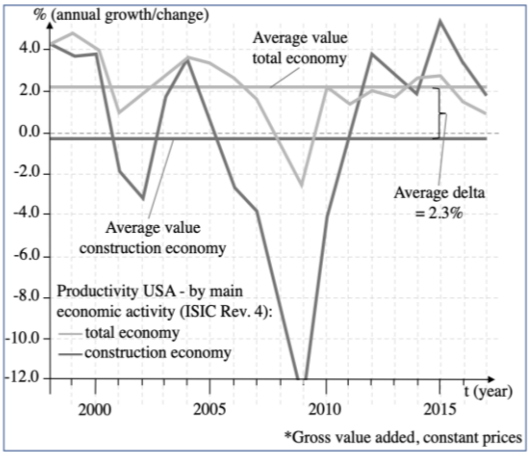


Figure 2. Annual productivity ratings of the US; total economy vs. construction economy; Figure based on [10].

2. Literature Review

An investigation by Kuenzel et al. (2016) indicated that close to 90% of the analyzed construction projects suffered from coordination problems and unsuccessful project management and exceeded project deadlines [11]. In the same year, Oesterreich et al. (2016) revealed organizational issues in construction projects to be a fundamental cause of project failure [2]. Oppong et al. (2017) discovered the insufficient commitment of stakeholders to the project to be an important reason for project failures [1]. Further investigative approaches have shown that planning issues, complications in project organization, and stakeholder disagreements allows projects to exceed their schedules and budgets. Increasing project complexity, constantly changing customer requests, and a wide variety of regulations result in even greater planning and execution efforts [3,12–14]. Moreover, the sophisticated technical requirements and high quantity of project participants greatly affect the deployment efforts in project management and control. Kim et al. discovered a further issue in 2018 that concerns project workflow interruptions caused by sloppy integration of the supply chain to the project execution process. Many planners, contractors, and small and medium sized enterprises (SMEs) source their information, goods, and services via highly fragmented, unstructured supply chains. Moreover, due to the use of mostly impossible just-in-time distribution options, the delivery of goods is rarely in line with the project's progression. Thus, the flow of a project is continually disturbed, which leads to significant project time and budget issues that negatively impact the project's outcome and customer satisfaction [3,4,11].

Sambasivan stated in 2007 that the issue of delays and schedule overruns in construction projects can be understood as a global phenomenon, with conclusive evidence in many studies [15]. A paper by Olawale and Sun (2015) evaluated several international investigations concerning exceeded costs and mismanaged time in construction projects; according to this paper, Hoffman et al. determined in 2007 that 72% of 332 public US-facility projects were delivered late, and 47% exceeded the project timeline by more than 4 months [16,17]. The German Federal Ministry of Construction conducted an analysis between 2000 and 2015 and found exceeded costs and mismanaged timelines in 300 building projects (>10 m EUR). Only 65% achieved their scheduled targets [18]. According to an investigation by Assaf and Al-Hejji (2006), 59% of 76 evaluated projects in Saudi Arabia were considered delayed [14].

However, the examples are not only negative. Salem et al. presented a construction project case study in 2006, where the application of specific agile organization and lean construction approaches (applied lean construction elements: Last Planner System; Increased Visualization; Huddle Meetings; First Run studies; 5S; Fail Save for Quality) brought the project's progression up to three weeks ahead of schedule [19]. Thomas et al. showed as early as 2002 that a significant reduction in project duration of about 30% is achievable through sustainable project management improvements [20]. Hanna et al. (2010) and Hwang et al. (2011) found advantages in thorough pre-planning, leading to improvements in the quality of work execution, increased productivity values, and a reduction in project duration [21,22].

Nevertheless, the main causes for project delays remain under investigation. Doloi (2012), Braimah (2014), and Larsen (2016), in addition to many others, investigated the significant impediments that directly impacted the project's schedule [13,23,24]. The results of these studies indicated weak design elements; poor project planning, site management, and project control; insufficient contractor experience; contract payment problems; equipment availability; weather/environmental conditions; and material supply issues as the primary causes for project delays [13,23,24]. A study by Gebrehiwet et al. (2017) revealed 52 of the most likely reasons for project delays; ineffective project scheduling ranked number two, behind deficient project planning [25].

This investigation shows the international situation of the construction industry and provides information about the general and fundamental problems in construction project planning and execution [7]. Weaknesses in project design and inadequate schedule and cost management appear to be of particular importance regarding the root causes of errors. The inevitable consequences of these differences between planned and actual values lead to unforeseeable and unexpected additional cost and time requirements and thus to an increasing risk of the projects success. In order to further investigate and narrow down the described causes, current project management methods and the most recent solution approaches will be examined in the following.

3. Current Common Project Management and Scheduling Approaches

To understand a project's timeframe, certain project management and scheduling approaches—mostly IT-aided and cross-industry applicable approaches—have been implemented in the construction sector during past decades [15]. The core objective of project scheduling is assigning the start and end dates for individual or cumulative activities and indicating when these activities must be finished to be delivered on time [26]. A valuable method to gather and structure the required project execution activities is given by the Work Breakdown Structure (WBS) method. This method has no time references but provides a general framework for schedule development and enables project management, monitoring, and control tasks [27]. A common and widespread scheduling tool is the *bar chart* or *bar diagram*—also known as a *Gantt chart* or *Gantt diagram*, which graphically represents the connection between planned and actual work performance and whether activities are on schedule, behind schedule, or ahead of schedule [26]. Further common methods include the Critical Path Method (CPM), Line of Balance (LoB), Linear Scheduling Method (LSM), and a Network diagram [28–31].

First and foremost, these tools are based on the *waterfall* principle whose main characteristic is strictly hierarchical embossed organization (priority based) according to the ratio between a chronological task order and appropriate task durations. Each task obtains a clearly defined start- and end-date; dependencies on other tasks can then be determined [31]. Waterfall systems operate according to the push principle, which releases tasks, materials, or information into preassigned procedures or scheduling systems [32]. This method is ideally suited for projects with consistent or repetitive proceedings and recognizable long-term interventions due to regular organization [33]. Due to the predefined structure that is additionally required and/or was previously unconsidered, subsequently added activities could rapidly cause postponements and disturb the flow of a project. Tory et al. stated in 2013 that schedules should be dynamic documents, which can frequently be changed and adjusted in accordance to the project's progression and its various requirements [34]. In 2005, McKay and Wiers (2005) indicated that the amount of dynamic and unpredictable activities and the capacity for compensation should be considered when the scheduling method for a project is determined [31,35]. Thus, a significant disadvantage of the waterfall system is its non-dynamic ability to react quickly to fast-track changing procedures or ad hoc operations triggered by unpredictable events during a project's life cycle. Disregarding these disadvantages, waterfall-based scheduling methods are still widespread in the construction industry [34].

This system is contrasted by the agile methodology, which follows a maximum dynamic mode of operation. Project requirements and tasks are gathered and listed in the initial phase. An iterative process—consisting of task planning, execution, and revision steps—defines the project's organizational structure. Intermediary assessments can also be implemented to revise short-term activities [36]. Sanchez et al. (2001) described agility as a cooperative and synergetic strategy that organizes the processing and delivery of customer-specific high-quality goods and services, even in dynamic or unpredictable project environments. Well-structured organization combines constituent project participants into multi-skilled and cross-functional teams with participating members from both (internal/external) customers and suppliers [37]. The purpose of this method is to streamline project management efforts and to keep flexibility high, even with changes in late project stages [32]. According to Sacks et al. (2010), the basic methodology behind agile management is the lean approach, which was implemented in and adapted to the construction sector to "reduce variation, improve coordination, implement flow, establish pull, and to reduce various forms of waste in construction projects" [38]. The potential deficiencies of agile methods include difficulty in predicting a project's progression and missing the transparency of timescale objectives due to the flexible organization of task execution [7,39]. With the introduction of the Last Planner System (LPS) in 1993/94, the first official agile method was applied to the construction industry [7]. The implementation of master- and phase-schedules have contributed to more organized project execution and have connected production targets with project work structures. Key advantages of the LPS include significant improvements in information exchange and strengthening of the cooperation between project/site managers and foremen, who gather in monthly and weekly meetings to solve upcoming issues before they become critical. Due to its agile characteristics, the LPS improves schedule reliability and is ideally suited for complex, dynamic, and uncertain project conditions [40]. However, a critical aspect of this method is its limited implementation possibilities, as the system was developed mainly for project execution duties and is thus primarily applicable to the execution phase of a project. Further, the insufficient establishment of the lean principle to pursue perfection is a persistent issue, which prevents the continuous improvements and optimization of upcoming projects. Weekly work plans do not provide provisions to conduct any experimentation; thus, the LPS learns from failure rather than from success [38]. Moreover, the knowledge gained through work execution is not stored and organized in databases and cannot be used in further projects [33,34,39]. According to Sacks et al. (2010), the LPS achieves a reduction in variation through the early consideration of upcoming issues but misses the implementation of pull by disregarding important indications (signals) generated by downstream operations. Additionally, the LPS rarely provides a clear evaluation of the actual project status, which may cause imprecise project status indications [38,41]. In order to optimize this kind of project management, the KanBIM method was proposed, which extends the Last Planner system by the use of a 3D Building Information Model, which allows to visualize the construction progress and obstacles in the construction process through Kanban signals and symbols [7,38,42].

The innovation to use virtual 3D CAD/BIM models for the representation of project performance was initially suggested by Songer et al. (2000), who investigated workflow modeling's relationship with virtual 3D modelling to visualize project performance [43]. Later developments produced the 4D method, which connects the virtual 3D model with time-related activity information [44]. Further common approaches have added an additional dimension to offer the benefits of a virtual 3D CAD model that includes the appropriate project cost elements alongside project related time information (4D). This method is commonly referred to as the 5D methodology [45–47]. Figure 3 shows an example of the 5D BIM approach were the allocation of the 3D model objects to the corresponding Bill of Quantity (BoQ) positions as well as schedule activities is conducted manually.

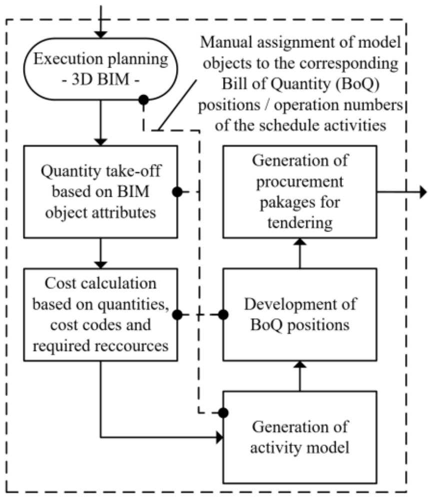


Figure 3. The 5D Building Information Model (5D BIM) approach.

To assign work execution tasks to specific project model parts, Sacks et al. proposed the use of *fine-grained* activity information from a 3D model and the creation of work-packages, which can be split into trade-specific tasks that are manageable by individual workers. These packages are represented within this model by Kanban-symbols or as a group of highlighted objects [38]. Each contractor has to develop an individual trade-specific weekly work plan, which is later synchronized with a general (project-wide) weekly work plan. The "*Kanban card type pull flow control signals and Andon alerts*" display the constraints and workflow interruptions within the 3D model [38]. To avoid interruptions of the execution process, daily on-site inspections and adjustments are conducted by a team of trade-leaders and site managers. The actual project performance statuses are displayed live by the 3D models on various screens at the construction site [38].

Although this methodology improves the reliability of task delivery and reduces variability, it enlarges project management targets drastically, as trade-specific work plans must be developed weekly before trade-related tasks can be negotiated due to synchronization with project-wide weekly work plans. In this way, tasks with lower priority have negative effects on the decision-making process and encourage undesirable discussions. In this scenario, the highly productive and efficient weekly Last Planner meetings threaten to disappear. Moreover, a trade-specific and project-wide evaluation and coordination of constraints could cause unavoidable latencies, which are critical for proper performance status indication and may hinder the flow of the project.

This analysis demonstrates that previously described methods have yielded significant improvements for individual and specific project characteristics. Approaches for repetitive and dynamic process requirements provide helpful possibilities to handle various project execution operations, even with the implementation of fine-grained activity information from 3D models to display the work in progress. Some important factors, however, retain considerable potential for improvements but have been widely disregarded: (a) close cohesion between predesign/design information (3D model objects) and project related time and cost values could be achieved via a tight interdependence between the 3D model objects, the corresponding Bill of Quantity (BoQ) positions (costs), and appropriate execution durations—this is, in the following, referred to as the *5D Building Information Model (5D BIM)*; (b) by using the early division of the 5D BIM into clearly defined project sections (PS), the determination of executing relevant target dates could provide a basic grid, which is necessary to structure the agile-organized project execution; (c) the actual required resources and values, determined during work execution (e.g., the actual required execution durations of specific tasks/actual used resources etc.) could be compared with the planned values. On this basis, continuous improvement strategies could be implemented, thus contributing to sustainable improvements of the planning accuracy of future projects.

4. The *5D-PROMPT* Method

Since the current scientific literature does not provide a coherent solution that combines the advantages of the previously described methods and the unexploited possibilities, this paper presents a comprehensive approach to obtain these goals. This new concept is referred to as the *5D-PROMPT* method. Its main objective is the sustainable reduction of both the deviation and variation between as-planned and as-built construction project targets. The key process consists of:

- Fully applied 5D BIM planning (5D BIM setup, including the interlinkage of 3D model objects, scheduling activities, and corresponding costs);
- Model split—the definition of approximately equal-sized project sections;
- Virtual construction process simulation (waterfall-based);
- Virtual construction process optimization (elimination of collisions/utilization of free resources);
- The establishment of execution-relevant target dates (project start and end date; project section-based delivery dates (milestones); monthly/weekly review/preview meetings);
- The setup of an agile structured project execution planning board;
- Agile work execution organization/agile work execution;
- Determination of the as-built data (quantity-/cost-/time-based effort values);
- The evaluation and comparison of as-built/as-planned data;
- The repatriation of as-built data/update of planning data (companywide);
- 5D BIM-based progress status indication (highlighting of model objects).

A careful selection of these principles is summarized in a multi-crossed hybrid system that operates throughout all project phases in accordance with the individual process requirements.

To provide a broad understanding of the key improvement aspects of the 5D-PROMPT method, and to explain essential enhancements a common and widespread construction design and execution process example should be introduced previously. Its basic structure represents an assumed process of conventional (3D CAD model-based) project planning, tendering, and contracting of subcontractor services, as well as a waterfall-based organization of the work execution. The process is characterized by its appropriate process steps, which are illustrated in Figure 4.

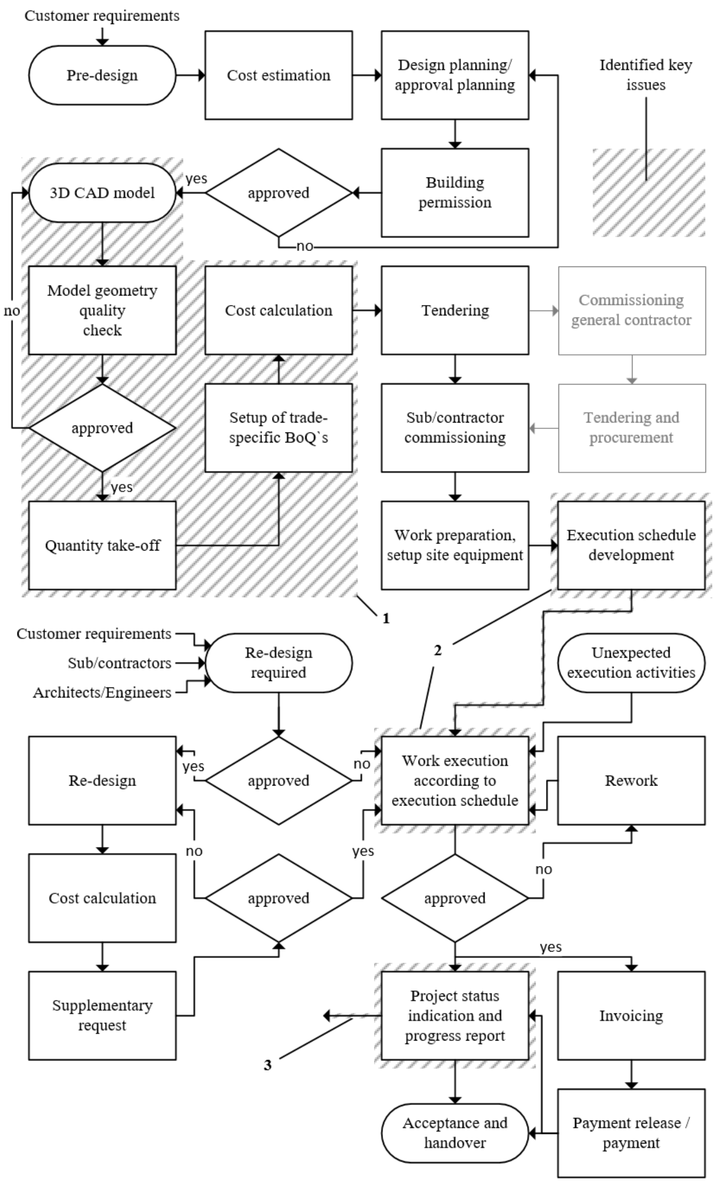


Figure 4. Initial situation: currently common construction design and execution process example.

Potential weak points and missing interconnections that are critical to a coherent and interconnected workflow are represented by the numbers 1–3 and are described as follows: (1) The significant issues include the missing interconnection between the individual 3D CAD model objects/elements, appropriate schedule operations, and the corresponding BoQ positions. In addition, the construction process sequence is not corrected or optimized by simulation. Thus, the project design, project costs, and execution time threaten to drift apart over the course of the project, which will impede project control and are critical to project success; (2) a detailed development of the work execution schedule often takes place immediately before the execution phase starts. Moreover, the utilization of a slightly flexible waterfall-based scheduling method appears inadequate for the numerous unexpected and unpredictable on-site incidents. Further, permanent cooperation between the work execution schedule and on-site operations is required; (3) significant deviations between the planned and used recourse values could be reduced by implementing specific information feedback-loops, which report back crucial as-built values/information in accordance with Deming's Plan-Do-Check-Act cycle [7].

Based on the previously presented workflow, Figure 5 demonstrates the key enhancements and general operating principles of the 5D-PROMPT method. This method consists of five main sections: (1) fully applied 5D BIM planning process; (2) IT-supported connection of the 3D BIM objects, with the associated BoQ positions as well as schedule activities by utilization of linking elements. (3) early determination of project duration and project sections (PS) and definition of target dates for PS deliveries; (5) agile project execution organization according to predefined target dates; and (5) intermediary information feedback loop implementation for project status indication and target/actual comparison by the 5D BIM as the *single source of truth* (*SSOT*).

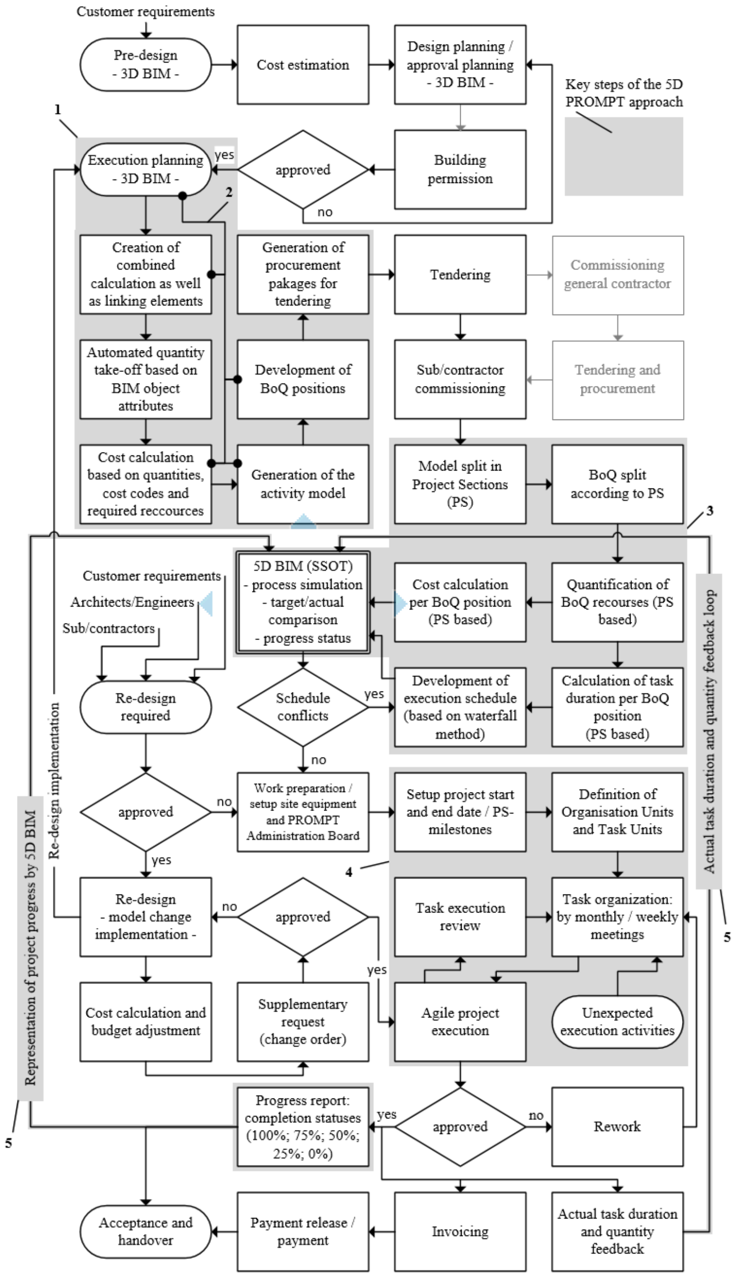


Figure 5. Workflow of the 5D-PROMPT method.

5. Mode of Operation

5.1. 5D BIM Planning Process

To take advantage of the 5D BIM-based planning approach, it is crucial to generate the entire project design using a virtual 3D BIM model (Figure 6(①)). The individual BIM objects are assigned to their corresponding BoQ positions, which contain product characteristics, costs per unit, and quantity information (Figure 6(②,③)). The technical implementation of the 5D BIM approach, which is applied within the 5D-PROMPT method, uses a link position to interconnect the 3D model objects with the associated BoQ positions as well as schedule activities. It is considered as a key element that ensures a close connection between the individual planning elements and contributes to prevent design, project cost and construction time from drifting apart. This innovation was developed by RIB Software SE within the software solution iTWO 4.0. In order to achieve the optimum performance of the 5D-PROMPT method, this methodology was used accordingly. Time-specific effort values, which provide information about the time needed to execute the required construction tasks (activity duration), are extracted from the BoQ position and transferred to a corresponding activity operation in a waterfall-based schedule application, e.g., Gantt Chart (Figure 6(④)). Although the 5D-PROMPT method stipulates agile organized construction work execution, a waterfall-based schedule is developed during the initial project planning phase to determine the project/activity duration and provide a theoretical project execution simulation. In this way, specific start/end dates are assigned to each scheduled activity. To achieve an optimized execution workflow, the methodology of the Critical Path, including the forward pass/backward pass, float calculations, and fast-tracking options, is applied appropriately. In this way, the 5D BIM planning approach enables a virtual construction process simulation, with the concurrent process of project costs and activity durations.

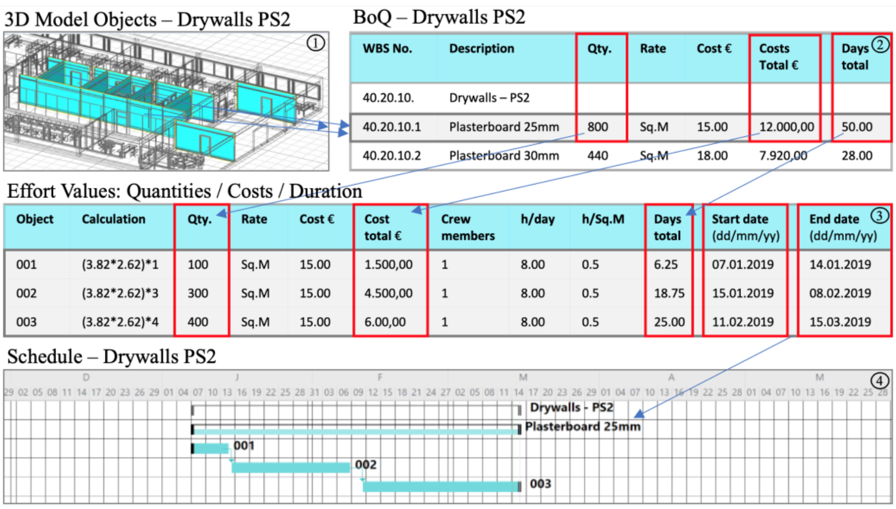


Figure 6. Technical description: 5D BIM planning approach.

5.2. Determination of the Project Duration and Project Sections (PS) and the Definition of Target Dates for PS Deliveries

To form the conditions for an aspired agile organization of construction execution, a basic grid should determine the direction of the work proceedings. For this purpose, the 5D BIM is split horizontally and vertically in *approximately* equal sized Project Sections (PSs). The corresponding BoQ positions, and schedule activities are divided and re-compiled appropriately. After schedule reorganization, the project start/end date (Project Frame—PF) and the start/end dates of each PS can be determined. Any other information provided by the waterfall-based schedule has no further use over the remaining course of the project. Applied effort values within the project planning phase are updated/corrected via actually used (as-built) values.

5.3. Agile Project Execution Organization According to Predefined Target Dates

A core aspect of agile organized work execution is the collaborative competence of the contractors (capacity for teamwork) involved in the execution process. All construction trades should be tendered and contracted/subcontracted at this time of the project; specific project organization requirements must become an integral part of the contractor/subcontractor agreements. To manage/organize project execution onsite, an agile execution organization board (hereafter referred to as the *PROMPT Administration Board*) is formed in close cooperation between the foremen and site/project-manager. The basic approach in this method is similar to the Last Planner/Scrum/Kanban project organization plans or boards; however, the present method differs in its setup and arrangement [39,48]. The PFs and PSs define the general project guidelines and determine the deadlines for PS/total project delivery. Thereafter, fixed time periods are established to manage/review on-site work execution in a monthly and weekly sequence:

- Organization Unit (OU)/Billing Period—monthly cycle
- Task Units (TU)/Report Period—weekly cycle

The form and concept of the PROMPT Administration Board are explained in Table 1.

Table 1. Leading structure for development of the PROMPT Administration Board.

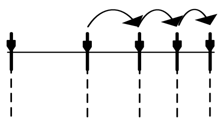
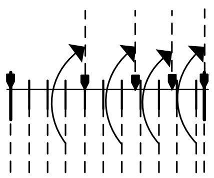
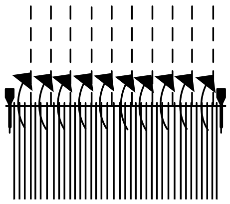
Board Structure	Key Units	Project Management Compendium
Project Start and End Date 	Project Frame (PF);	PROMPT Administration Board setup; Set project start-date/end-date for total project duration (derived from waterfall-based project schedule); Aim Project Sections (PSs)
	Organization: administration kick-off meeting	
Project Sections 	Project Sections (PSs);	Set Project Section milestones: start-date/end-date (derived from waterfall-based project schedule); Superior task summary; Agile reconciliation of task order per PS (end-to-front organization); Feasibility evaluation—compliance with PF; Commitment to agreements
	Organization: Administration kick-off meeting	
Organizational Units (monthly review of PS compliance)	Organizational Units (OUs)	Set Organization Unit start-date/end-date (duration: 1 month—determination of fixed weekdays is compulsory due to synchronization with weekly Task Unit sequence: 1 month ≈ 4.4 weeks; Set start date: e.g., every last Friday of each month; Set end date/due date for monthly meeting: e.g., every last Thursday of each month; Agile reconciliation of target order per OU (end-to-front organization); Definition of execution scope per Task Unit (TUs are based on model sections: rooms; slabs; objects, etc.); Advanced organization of complex/risky tasks; Feasibility evaluation—compliance with Project Section milestones; Commitment to agreements (post-its)/review of finished Task Units/evaluation of target agreements
	(subordinated organization of project execution tasks);	
	Organization: monthly meeting	
	Billing Periods (period of partial invoicing)	Set Billing Period start-date/due-date: equivalent to OU dates; Invoicing according to finished, reported and approved Task Units

Table 1. *Cont.*

Board Structure	Key Units	Project Management Compendium
Task Units (monthly review of OU compliance)	Task Units (TUs)	Administration task definition—Set Task Unit start-date/end-date (duration: 1 week—determination of fixed weekdays is compulsory due to synchronization with monthly meeting of Organization Unit—in this example: every last Thursday of each month); Set start date: e.g., every Friday of each week; Set end date/due date for weekly meeting: e.g., every Thursday of each week; Agile reconciliation of targets per TU (post-its); Specific organization of complex/risky tasks; Feasibility evaluation—compliance with Organization Unit sequence; Commitment to agreements/review of finished model sections/evaluation of delays and target agreements
	=∑ pre-defined model sections (rooms/walls/slabs, etc.) that could be finished within one week by a trade-specific execution team;	
	Organization: weekly meeting	
	Report Periods (weekly project execution performance report)	Set Billing Period start-date/due-date: equivalent to TU dates; Reports according to finished and approved Task Units—Task Unit finished (100%); Task Unit in progress (50%); Task Unit open (0%)

The task organization is graduated from general to particular. Appropriate descriptions are provided in accordance with the specific levels of organization. The setup and formatting of the organizational structure (PROMPT Administration Board) is done during an administration kick-off meeting conducted by the execution team members (foreman/project manager—contractor side/project manager—client side). The workflow and superstructure are outlined in Figure 7. Since the project start/end dates and milestones for PS delivery are attached to the administration board, the Organizational Units and Task Units can be defined.

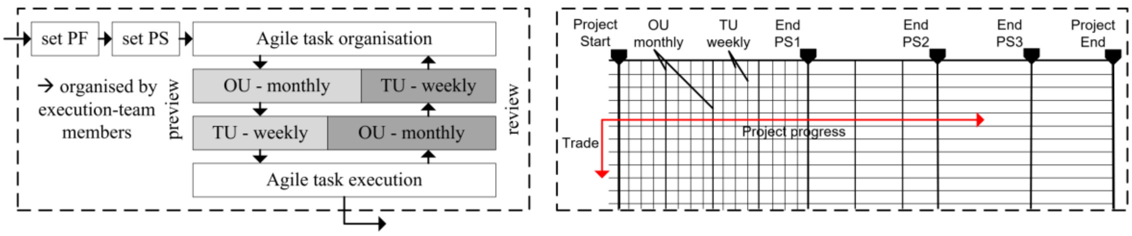


Figure 7. Setup and superstructure of the PROMPT Administration Board.

Participation in monthly/weekly meetings is compulsory for each of the execution team members. Individual arrangements and general agreements determined during these meetings must be accomplished within the envisaged time frame.

5.4. Intermediary Information Feedback Loop Implementation for Project Status Indication and Target/Actual Comparison

The construction progress is evaluated and updated during the weekly meetings (Report Period) based on the actual completion status values of the planned (trade-specific) targets. The completion status values are 100%, completed; 50%, partly completed; and 0%, pending. The actual status values are displayed in colored markups (green; yellow; grey) by the 5D BIM. Invoices can be issued in accordance with the Billing Periods (monthly). The basis for payment approval is the actual (trade-specific) competition status of the accumulated monthly activity performance.

To achieve sustainable improvement of the planning accuracy, substantial deviations between the planned and actual execution durations are identified and evaluated by the execution team members and reported back to the project planning department to implement a sustainable correction process for time-based calculation matters. Furthermore, deviations between the planned and applied resources can be determined immediately. Thus, the planning accuracy for future projects could be improved considerably.

6. The Comparative Case Study

An initial implementation and performance test of the 5D-PROMPT method was conducted using an actual practice construction project as a comparative case-study. To pre-classify the workability and expected benefits of the new approach (and to make it comparable to previous methods), one construction project was carried out according to conventional planning and execution methods, as described in the process chart in Figure 4 (hereafter referred to as Project A). During the same time period, an equivalent construction project was carried out according to the 5D-PROMPT method, as described in Figure 5 (hereafter referred to as Project B).

The performance values of both methods were determined using special Key Performance Indicators (KPIs—listed in Table 2) measured during/after the execution phases of both projects and subsequently evaluated by a multi-criteria analysis. The required KPIs were selected based on the findings of the literature study and an analysis of the current state project management approaches.

Table 2. Definition of Key Performance Indicators (criteria); reference units, weighting factors, and determination to target a higher or lower performance value.

Key Performance Indicators—Project A; B	Total	Per trade	UoM	Adjustment Requirements/Remarks	Weightage Factor (ω_j') b	Category **
Project duration *	x	—	CW	Project comparation criteria—Δ < 20%	—	—
Gross floor area (GFA) *	x	x	m2	Project comparation criteria—Δ < 20%	—	—
Gross volume (GV) *	x	x	m3	Project comparation criteria—Δ < 20%	—	—
Construction costs *	x	x	€	Project comparation criteria—Δ < 20%	—	—
Average exceeding of construction units	x	—	%	considered: factoring errors by domino eff.	0.25	n-b
Value of cost overruns	x	x	€		0.25	n-b
Value of deadline exceedings	x	x	CW	classification: unprediced/customer wanted	0.15	n-b
Value of supplements/planning changes	x	x	€	classification: unprediced/customer wanted	0.1	n-b
No. of supplements/planning changes	x	x	No.		0.02	n-b

Table 2. *Cont.*

Key Performance Indicators—Project A; B	Total	Per trade	UoM	Adjustment Requirements/Remarks	Weightage Factor (ω_j') b	Category **
No. construction interruptions	x	x	No.		0.03	n-b
No. of disability complaints	x	x	No.		0.03	n-b
No. of default notifications	x	x	No.		0.03	n-b
No. of construction defects during execution	x	x	No.	classification: self-inflicted/not self-inflicted	0.02	n-b
No. of construction defects after handover	x	x	No.	classification: self-inflicted/not self-inflicted	0.02	n-b
Project commitment of stakeholdersstrongly disagree 1 |2 | 3 | 4 | 5 strongly agree	x	—	Grades	Grade system (*Likert-Scale* [49])	0.05	b
Injuries to workers	x	—	No.		0.05	n-b

* Criteria were used to determine the comparability of Project A and Project B. ** b ≙ beneficial—higher performance value is desired; n-b ≙ non-beneficial—lower performance value is desired.

Project A and Project B were carried out by the general contractor company Heinrich Schmid GmbH and Co. KG during the years 2018/19 (Location: South Germany). Twenty-one trades were planned and executed by the project stakeholders over a period of 11 months for each project. As a comparison of the two construction projects would have led to inaccuracies due to a lack of absolute equivalence, a reference value was introduced as a benchmark for data collection. In this study, it is assumed that the process sequence and implementation of Project A are generally known. Therefore, the following section will only describe the procedure for the conduction of Project B. However, to provide a better understanding, the basic process steps of both projects are compared in Table 3.

Table 3. Overall process steps of Project A compared to Project B.

Project Phase+D9:F22	Process Steps-Project A	Process Steps-Project B
Design	2D/3D CAD design 2D/3D-based quantity take-off * BoQ development and cost calculation * Determination of execution activity effort values * Rough estimation of execution durations	3D BIM design 3D BIM-based quantity take-off 3D BIM-based BoQ development linked to model objects 3D BIM-based schedule development linked to model objects 5D Building Information Model split (project sections) 5D BIM-based construction process simulation/optimization
Tendering/Contracting	Software-based tendering and contracting	Intergarted, software-based tendering and contracting
Execution	Construction execution schedule development (waterfall-based) * Construction work execution based on Gantt-chart Work organization and controlling by individual site manager	Agile work organization and controlling - team-based Agile work execution and management 3D model-based execution status representations As-built information feedback loops

* without model linking.

As previously described, the design of Project B was based on a 3D BIM. This model was provided by Contelos GmbH, a virtual-modeling company. The construction software developer RIB Software SE provisioned the software tool iTWO Baseline, which was used to create the required interconnections between the individual model objects, the corresponding BoQ positions, and scheduling activities.

Furthermore, the model split operations, construction process simulation/optimization, the tendering and contracting of sub-contractor services, and 3D model-based execution status representations were conducted/developed by this software. To minimize the risk of method failure, in addition to the 3D BIM, conventional 2D CAD project plans were also created and kept available for execution.

Since the 5D-PROMPT method was introduced to the project stakeholders, continuous team coaching, and individual training were required to acclimate the participating members to run the project. To ensure a solid foundation, all project-related contracts had to comply with the agile project's execution requirements. The modeling company was required to elaborate the 3D BIM to confirm the modeling guidelines of the applied 3D modeling software (Revit) and to make use of a harmonized project-wide BIM attribution. A substantial measure was the awarding and contracting of all execution trades, which had to be completed before work execution started. Next, the *execution organization team* was formed, consisting of foremen, crew leaders, site managers, and the project leader. This team performed the setup of the PROMPT Administration Board using time-regulated "project start and end date as well as milestone date" information, which was determined by the waterfall-based construction execution simulation. Moreover, monthly/weekly time periods for the Organizational Units (OUs) and Task Units (TUs), were added to the board to establish a static structure for the work execution organization.

After work execution started, the team determined, confirmed, and evaluated both upcoming and finished work execution tasks during monthly/weekly meetings. Daily work performance monitoring ensured proper target/actual provisions and provided information about the required execution durations. Actual building statuses were represented by highlighted objects in the 3D BIM. Deviations between the planned and required time and cost values were evaluated and gathered in a database to help make future project planning more precisely predictable and reliable. The core process of the case-study is represented and described in Table 4.

Table 4. Integrated software application and practical 5D-PROMPT workflow implementation.

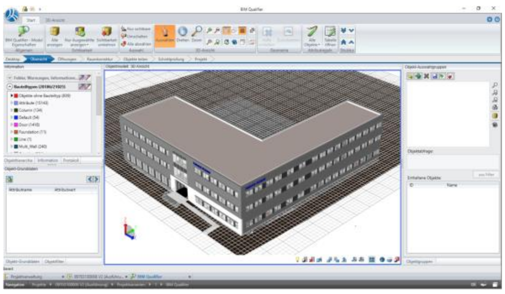
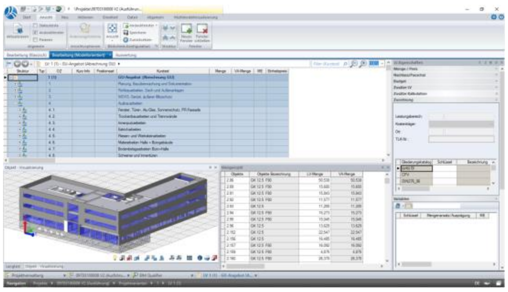
(a) 3D BIM design and Model Check	Note
	After the 3D BIM was designed using the 3D BIM capable software Revit®, the model was uploaded to iTWO Baseline and checked for errors and comprehensiveness via the integrated BIM Qualifier tool. This picture shows the 3D BIM
(b) BoQ development and connection between BoQ positions and model objects	Note
	The second step was the development of the individual BoQs, including model-based quantity take-off (QTO) and cost calculations based on resource-specific effort values. The BoQ positions were interlinked closely with the individual model objects.

Table 4. *Cont.*

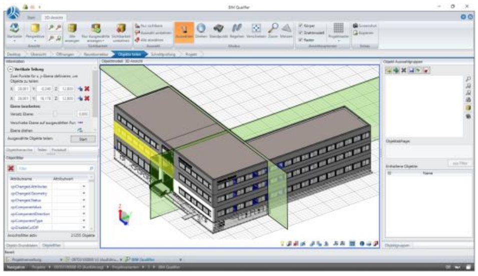
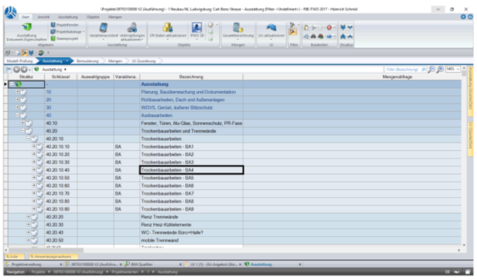
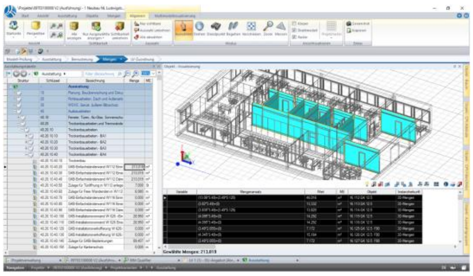
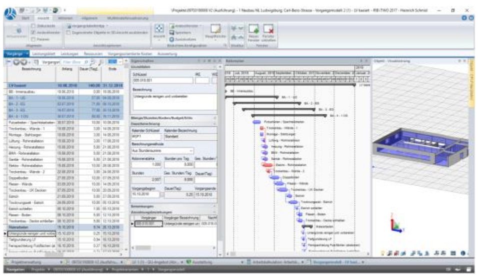
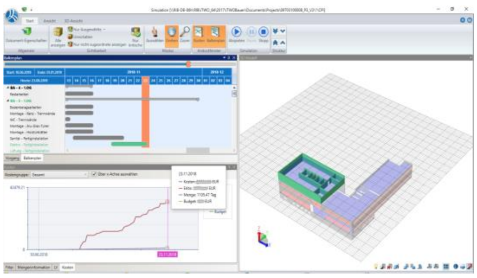
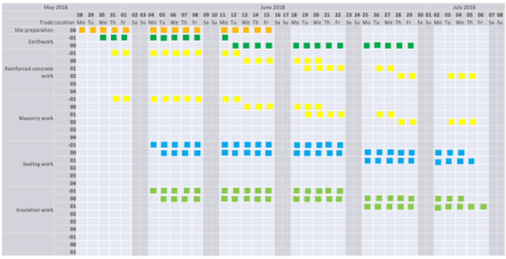
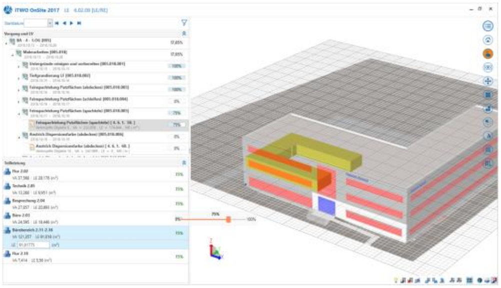
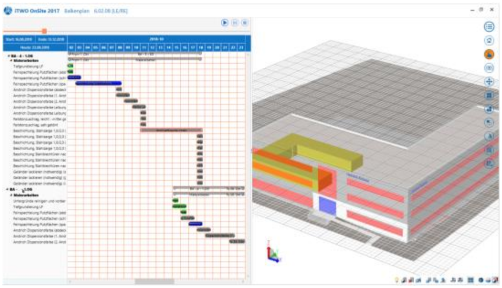
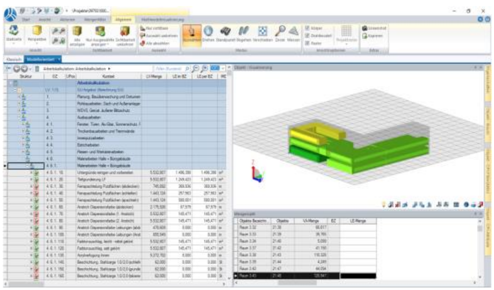
(c) Model split	Note
	To pre-define the course of the agile organized construction work execution, the model was split into approximately equal sized Project Sections (PSs). This was done using the "Split Model" option.
(d) BoQ split	Note
	The individual BoQs were split according to the number of Project Sections; the BoQ structure remained unchanged; quantities were distributed in the next step. ⇒ 9 Project Sections ≙ 9 BoQ sections.
(e) Quantity distribution	Note
	The model object quantities and the assigned BoQ-positions (including resource effort values, corresponding costs, and execution durations) were divided and distributed based on the related Project Sections.
(f) Development of the waterfall-based construction schedule	Note
	Next, the construction activities and associated execution durations were consecutively and chronologically listed in a waterfall-based project schedule chart. In the following step, the individual scheduling activities were linked to the corresponding model objects and BoQ positions.
(g) Virtual project simulation and process optimization	Note
	The project execution process was simulated, tested for any collisions/bottlenecks, and optimized accordingly. Moreover, the project start and end dates and milestones for PS delivery were determined.

Table 4. *Cont.*

(h) Agile project planning *	Note
	Setup of the PROMPT Administration Board: Transfer of the Project Frame and PS milestones from the waterfall-based project schedule chart. Implementation of Organizational Units and Task Units. Team-based agile work organization and review (→ Table 2) * schematic illustration due to the German project language.
(i) Work in progress measurements	Note
	Next, the Task Unit completion statuses (100%; 50%; 0%) were continuously captured onsite, accompanying the agile organized project execution. This was done via the integrated iTwo OnSite® software application. On this basis, trade-specific invoices were generated in accordance with the Organizational Units/Billing Periods.
(j) As-planned/as-built comparison and Feedback Loop implementation	Note
	Using the OnSite progress assessment, the actual used quantities/resources and costs were determined. These values were compared to the planned values. Deviations were reported back to the project planning department to be used for quantity/resource effort value updates. In this way, continuous improvement ensures a continual increase in future planning accuracy.
(k) Work in progress representation	Note
	The 5D-PROMPT workflow culminated in the project performance status representation, which was continuously shown by the 5D BIM. The model objects were highlighted by different colors according to the progress status (e.g., 0% grey; 50% yellow; 100% green).

7. Results and Multi Criteria Analysis

To make the two projects comparable, the reference value for the collection of data was set to 1000 m^2 GFA (Gross Floor Area). All measured values were related to this factor. The planned duration of both projects, including planning, tendering, contracting, and execution, was 11 months. To increase the comparability of the two projects, both projects were divided into construction sections of an approximately equal size. These sections were required to optimally allocate the scope of work and to serve as reference points for determination of the project's process status indication.

Project B was completed within the planned construction period. Each construction section was also completed on time, so each predetermined milestone passed on time. Deviations caused by the estimated values determined during the project planning phase were compensated by the agile construction process organization. Moreover, the implementation of the enhanced 5D-BIM approach has contributed to a considerable reduction of the deviations between the as-planned and as-built values. Project A exceeded the planned end date with a delay of about 4 weeks. The project milestones were passed, on average, 3–5 days later than planned. This resulted in a shift of the entire schedule and caused the final deadline to be significantly exceeded. At first glance, Project B matched the budget; however, additional and unexpected extra costs for necessary tablet/computer hardware and servers, including maintenance, hotline, and update services, were required due to the implementation of the new methodology. These costs amounted to a total of EUR 22,825 net per 1000 m^2 per year for Project B. This resulted in an actual cost overrun of 6.04% for this Project. The cost overrun of Project A was 16.2% in total for the reference value of 1000 m^2. This was caused by supplements due to inadequate planning, rework and defect management and the extended construction period (extra costs for provision of site equipment and staff).

To obtain the preliminary assessment of the influence of the new method in terms of its enhancements to project performance, accuracy in project planning, and schedule and cost reliability, a Multi Criteria Analysis was conducted. Based on the two alternatives, Project A (i_A) and Project B (i_B), and the predefined analysis criteria (j_n) previously described by the KPIs (see Table 2), an evaluation matrix was developed. Here, the cell variables represent the project-based performance value (X_{ij}) of each criterion.

To avoid assessment issues and to achieve comparable analysis results, the deviating units of the measurements of the criteria to be compared were unified, and linguistic terms of classification were assigned to a number-based performance value scale. Furthermore, normalization of the analysis matrix was required to obtain only numerical values without any units.

The allocation of each criterion into "beneficial—higher performance value is desired" (e.g., commitment of involved stakeholders) and "non-beneficial—lower performance value is desired" (e.g., exceeding of final project deadline) was next conducted, and the normalized performance value (X'_{ij}) of each cell had to be calculated. For this purpose, the following formulas were applied based on the criteria classification: "beneficial" or "non-beneficial". The minimum and maximum performance values were derived from the lowest and highest performance values of each criterion:

$$\text{It applies } \rightarrow X'_{ij}(beneficial) = \frac{X_{ij}}{Max\left(X_{ij}\right)};\ X'_{ij}(non-beneficial) = \frac{Min\left(X_{ij}\right)}{X_{ij}}.$$

Since the analysis matrix was normalized, a weighting factor (w'_j) was assigned to the normalized performance values (X'_{ij}) of each criterion $(\sum_{j=1}^{n} w'_j = 1)$ (see Table 2) to classify its influence on schedule and cost reliability, accuracy in project planning, and project performance. Each normalized performance value was multiplied by the assigned weighted factor to obtain the weighted normalized analysis matrix.

To calculate the absolute performance scores of Project A and Project B, each weighted normalized performance value (X''_{ij}) of each Project was cumulated. The entire calculation of the performance score per alternative $((i_A)$ and (i_B) (Project A; Project B)) can be described by the following formula:

$$performance\ score_{(i)} = \sum_{j=1}^{n}\left(\frac{X_{ij}}{Max\left(X_{ij}\right)}\right) * w'_j + \sum_{j=1}^{n}\left(\frac{Min\left(X_{ij}\right)}{X_{ij}}\right) * w'_j.$$

After the collection of all measurement data related to the respective Key Performance Indicators and the evaluation of all values, a total performance score of 0.38 was calculated for Project B. For Project A, the score was 0.12. To evaluate the significance of these values, the ranking scale shown in Table 5 was used. This scoring model is generally applied to assess alternatives based on several quantitative and qualitative criteria, objectives, or conditions. It is used to analyze a set of complex alternatives to order the elements of the set according to the analysis preferences based on a multidimensional target system. The order is represented by the performance value of each alternative. The evaluation numbers follow a five-fold scale (in this case, 0.05 to 0.55), where a higher evaluation number stands for a superior evaluation (Table 6) [50–52]. As a result, the project planning and execution of Project B according to the 5D-PROMPT method could generally be rated as "good". In direct comparison, Project A could only be rated as "bad" according to the conventional project planning and execution method. This indicates a considerable improvement of construction planning and execution under the 5D-PROMPT method and suggests an immense enhancement of overall project performance. Further results and differences of both project organization methods are listed and explained in the following section.

Table 5. Evaluation Matrix—Determination of the performance value (X_{ij}). This method applies → $X_{ij} = performance\ value\ of\ the\ i^{th}\ alternative\ over\ the\ j^{th}\ criteria.$

	j_1	j_2	j_3
i_A	$X_{i_A j_1}$	$X_{i_A j_2}$	$X_{i_A j_n}$
i_B	$X_{i_B j_1}$	$X_{i_B j_2}$	$X_{i_B j_n}$

Table 6. Ranking scale [47].

Scale Values	Icon	Definition
0.45–0.55	++	very good
0.35–0.449	+	good
0.25–0.349	0	sufficient
0.15–0.249	-	less sufficient
0.05–0.149	–	bad

The comparison also shows that the number of construction defects during the construction phase of Project B was 82.6% lower than that of Project A. The costs for supplements and changes in planning due to the voice of the customer were also approximately 71.5% lower than those in the comparable project. The commitment of the participants to the newly introduced method of Project B was very high (Grade 5—*strongly agree*, from the Likert scale analysis [49]), but the commitment of the project execution team to the conventional method was also rated "high" (Grade 4—*agree*, from the Likert scale analysis [49]). The number of disability notifications and notices of default was three for Project A, while Project B was completely unaffected by these measures.

There was no absolute stop of construction work in either project. Moreover, an officially decreed construction stop was imposed in neither of the projects, and no workers were injured or killed during the construction process. The costs of implementing the new methodology of Project B were related to the following services: (1) introduction and training of the project organization method, (2) software teaching and training, (3) process consulting, (4) development of project-relevant master data, and (5) operational project support. These services were calculated proportionately according to the reference values of 1000 m2 per year and amounted to EUR 38,500 net in total. These costs include, as described above, the considerable additional costs for extra required hardware equipment and software-related services.

8. Discussion and Conclusions

The initially mentioned productivity growth of the American and European construction sector indicated international structural weaknesses and considerable performance deficiencies over the past twenty years. These preliminary graphs (Figures 1 and 2) represent only a portion of the international situation. Further statistics could be included, but a deeper insight into international conditions was garnered through the literature study. The literature provides a relatively far-reaching overview of the current problems of the construction industry but often refers to different project variants that cannot be compared directly or can only be compared with difficulty. Although some studies included in the literature review of this article show improvements in project organization methods due to advanced innovations, in many cases, these developments fall short of their goals, as they often relate only to the work execution phase and do not sufficiently account for essential criteria and possible improvements during the project design phase. At this point, the 5D-PROMPT method is intended to meet the requirements of transferring essential information from the design phase to the execution phase (e.g., current planning status of the BIM as a single source of truth; project timeframe and key milestones tested and optimized by simulation). In addition, the knowledge gained from the construction phase has to be reintegrated into the construction planning of future projects. The project organization method referred to as the *common* method in this article should only be understood as an example and is only one of countless other possible examples.

The comparative case study was conducted to obtain a preliminary and brief overview about possible improvements in project performance, accuracy in project planning, and scheduling and cost reliability through application of the 5D-PROMPT method. This was not a representative study, as only one sample for each criterion/alternative could be collected due to comparing only two projects. Nevertheless, a range of different Key Performance Indicators (criteria) were measured, which provided the study results with a certain significance. For the comparability of both projects, it was of particular importance that both projects were appropriately similar ($\Delta < 20\%$) and were carried out by the same executing company at the same time. The PROMPT administration board was used as an analog planning board within the case study. To avoid interface problems and a possible loss of information in future investigations, a digital planning board, fully integrated into the overall process, will be required. Automated functions based on a self-learning system should also be developed in future papers.

A main obstacle that emerged during the implementation of the project under the 5D-PROMPT method (Project B) involved defining the Task Unit (TU) content and the corresponding model objects. A general trade-by-trade definition was considered unusable since different trade specifications consist of various completion characteristics in terms of (a) the standardization of target unit measurements, (b) increasing deviations over long project execution periods, and (c) tracking of multiple correlated design changes. These issues were solved by the classification and alignment of trade compliant model sections, which are measurable, de-limitable, and directly extractable from the 5D BIM. This common problem (which is typical for agile organized projects with missing references for project target dates, deadlines, or time limits) was handled by properly determined project start/end dates and Project Section (PS)-related milestones. Thus, the course and frame of the project followed a clear structure and was traced by the participating stakeholders. To solve consequential coordination difficulties, the foremen of adjacent trades took part in the agile organization meetings and contributed to solving forthcoming issues.

The results of the case study indicated a considerable improvement of the objectives pursued. However, since only one project was counted as a sample, this study was relatively limited. Therefore, no statistical evaluation of the results was achievable. However, due to the large number of different criteria examined, it was possible to carry out a multi-criteria analysis, which provided a preliminary impression of the effectiveness of this method. The weighting of the multi-criteria analysis was particularly focused on the criteria that affect exceeding construction time and costs, as well as disruption-free construction processes. One experienced value concerns the oversized storage capacity of the server used for Project B. In future projects, this value this could be reduced considerably, thereby decreasing the direct project costs per 1000 m^2.

Generally, the technical implementation and feasibility of the proposed method was proven to be beneficial, and possible technical improvements have already been derived. To obtain a reliable evaluation of the effects of the entire 5D-PROMPT method, a series of projects must be carried out and examined in accordance with this method in future investigations.

9. Future Perspective

At the present stage, the 5D-PROMPT method indicates promising improvements in project organization and schedule reliability. Moreover, the cooperation of waterfall-, agile-, and lean-based process organization had a positive influence on the project performance. However, to evaluate the real advancements in terms of schedule reliability, project performance, and planning precision improvements, further research and empirical analysis is required. The appropriate project size that best fits the application of the 5D-PROMPT method should also be examined in detail.

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